Preliminary Project Execution Plan
for the
Neutron Electric Dipole Moment Project
(nEDM)

Project #MIE-06-EDM

at
Los Alamos National Laboratory
Los Alamos, New Mexico
managed by
Los Alamos National Security, LLC

For the U.S. Department of Energy
Office of Science
Office of Nuclear Physics (SC-26)

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Preliminary Project Execution Plan
for the
Neutron Electric Dipole Moment (nEDM)
At Oak Ridge National Laboratory
January 2007

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Change Log

Revision No.	Pages Affected	Effective Date
Revision 0	Entire Document	January 2007

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List of Acronyms and Abbreviations

AE acquisition executive
ANSI American National Standards Institute
BA budget authority
BCP baseline change proposal
CAD computer aided design
CCB change control board
CD critical decision
CDR conceptual design report
CDS central detector systems
CF conventional facilities
CP charge parity
CPM contractor project manager
D&D decommissioning and decontamination
DAQ data acquisition
DCD design criteria document
ORO Oak Ridge Site Office (DOE)
DOE Department of Energy
EA environmental assessment
EAC estimate at completion
EDM electric dipole moment
EIS environmental impact statement
ESAAB Energy Systems Acquisition Advisory Board
ESH&Q environment safety, security and health
ETC estimate to complete
EVMS earned value management system
FNPB Fundamental Neutron Physics Beamline
FONSI finding of no significant impact
FPD Federal Project Director
FTE full time equivalent employees
FY fiscal year
He3S ^{3}He Services
HQ DOE Headquarters
HV high voltage
IPT integrated project team
ISMS integrated safety management system
LANL Los Alamos National Laboratory
LANS Los Alamos National Security, LLC
LASO Los Alamos Site Office (DOE)
LDRD laboratory directed research and development
LHe liquid helium
LLP long lead procurement
M&O managing and operating
MIE major item of equipment
MOU memorandum of understanding
nEDM neutron electric dipole moment
NEPA National Environmental Policy Act
NNSA National Nuclear Security Administration
NOI EIS notice of intent
NP Office of Nuclear Physics (DOE)
NSAC Nuclear Science Advisory Committee
NSF National Science Foundation
OP funding type – operating expense
OPA Office of Project Assessment (DOE)
OPC other project cost
ORNL Oak Ridge National Laboratory
ORO Oak Ridge Operations
PARS Project Assessment and Reporting System (DOE)
PCR project change request
PEP project execution plan (federal document)
PPEP preliminary PEP (contractor document)
PSAR preliminary safety assessment report
PSO Program Secretarial Officer
QA quality assurance
R&D research and development
RF radio frequency
ROD EIS record of decision
SAD safety assessment document
SAE Secretarial Acquisition Executive
SAR safety analysis report
SC Office of Science (DOE)
SC-NP DOE Office of Science, Office of Nuclear Physics
SDB small/disadvantaged businesses
SNS Spallation Neutron Source
SQUID supercondcuting quantum interference device
TAT technical advisory team
TEC total estimated cost
TPC total project cost
U.S. United States
UCN ultracold neutron
VE value engineering
WBS work breakdown structure

1. Introduction

The neutron Electric Dipole Moment (nEDM) Experiment studies the fundamental space-time properties of the neutron, one of the building blocks of the matter that surrounds us. The apparatus looks for a very small difference in the precession rate of a neutron placed in weak magnetic field when a strong electric field is applied either parallel or anti-parallel to the magnetic field. Precession is a phenomenon by which the axis of a spinning object “wobbles” when a torque is applied to it. The observation of a difference in precession rate indicates that the neutron has an electric dipole moment and, therefore, violates the charge-parity (*CP*) symmetry. *CP*-violation may explain the matter excess in the universe. The proposed major item of equipment (MIE) in support of this experiment will allow the fundamental space-time properties of the neutron to be studied with up to two orders of magnitude greater sensitivity than ever before. This level of sensitivity does not exist in current and planned experiments and is necessary in order to measure the different rates of precession to sufficient accuracy to constrain existing theoretical models.

The experimental apparatus is being proposed by Los Alamos National Laboratory (LANL) and its collaborators from Oak Ridge National Laboratory (ORNL) and thirteen universities. The experiment will be located at the Fundamental Neutron Physics Beamline (FNPB) at the Spallation Neutron Source (SNS) Facility at ORNL. FNPB is unique in that it will provide the highest peak current of cold and ultracold neutrons (UCN) in the world. The FNPB is under fabrication with support from the Office of Nuclear Physics and is scheduled to be complete in 2010.

The nEDM Project constructs the apparatus required to execute the nEDM experiment. On November 11, 2005 Raymond L. Orbach approved the statement of Mission Need for the nEDM Project with a total project cost (TPC) range of $12.0M to $18.3M. The approval also designated the Associate Director for Nuclear Physics as the Acquisition Executive for this project with authority to approve all subsequent critical decisions.

This Preliminary Project Execution Plan (PPEP) for the nEDM Project provides overall guidance to the various project participants on the roles, responsibilities, and management interactions among the Department of Energy (DOE) Office of Science (SC), the DOE Los Alamos Site Office (LASO), DOE Oak Ridge Operations (ORO), the national laboratories, and the universities involved in the nEDM Project. The PPEP describes the coordination of efforts of the project team, including the processes and procedures used by the nEDM Contractor Project Manager (CPM) and Federal Project Director (FPD), to ensure that the project is completed on time and within budget. The PPEP defines the project scope and the organizational framework, identifies roles and responsibilities of contributors, and presents the work breakdown structure (WBS) and schedule. The nEDM PPEP also describes the formal change control process by which project cost, schedule, or scope may be revised in consultation with the FPD and the DOE Office of Science, Office of Nuclear Physics (SC-NP).

2. Mission Need

The mission of the DOE Nuclear Physics (NP) Program is to foster fundamental research in nuclear physics that will provide new insights; advance our knowledge on the nature of matter and energy; and develop the scientific knowledge, technologies, and trained workforce that are needed to underpin the DOE's missions for nuclear-related national security, energy, and environmental quality. To accomplish this mission, the NP Program supports the research of scientists, the operations of facilities and the development of forefront facilities and technology. These activities are carried out under the mandate provided in Public Law 95-91 that established the DOE, and assigns the NP Program the lead responsibility for federal support of fundamental research in nuclear physics.

The nEDM Project provides research capabilities that directly support the NP mission and address the NP Program Goal 05.20.00.00 to understand the evolution and structure of nuclear matter from the smallest building blocks, quarks and gluons, to the elements in the universe created by stars. One of the main objectives of this field is studying fundamental symmetry properties in nuclear systems. The nEDM experiment supports this goal by studying the fundamental space-time properties of the neutron, one of the building blocks of the matter that surrounds us. In 2003, the NSAC Subcommittee on Fundamental Physics with Neutrons characterized their findings on the nEDM experiment, "EDM is the experiment with the greatest discovery potential for the new fundamental-neutron-science beam line at the Spallation Neutron Source."

The possible existence of a nonzero EDM of the neutron is of great fundamental interest in itself and directly impacts our understanding of the nature of electroweak and strong interactions. The experimental search for this moment has the potential to reveal new sources of time (T) and CP-violation and to challenge calculations that propose extensions to the Standard Model. In addition, the small value for the neutron EDM continues to raise the issue of why the strength of the CP-violating terms in the strong Lagrangian is so small. This result seems to suggest the existence of a new fundamental symmetry that blocks the strong CP-violating processes.

The existence of a neutron EDM constrains a wide variety of theories of nuclear and particle physics. The nEDM Experiment will search for new physics in the CP-violating sector with a sensitivity of 1σ sensitivity of 1.4×10^{-28} $e{\cdot}$cm (Eq. II.7 of the CDR) or equivalently be able to set an upper limit of 2.3×10^{-28} $e{\cdot}$cm with 90% confidence. The increased sensitivity will permit researchers to probe CP-violation in the strong interaction at sufficient levels needed to help understand the matter/antimatter asymmetry of the universe.

3. Project Description

3.1 Overview

The goal of the current experiment is to significantly improve the measurement sensitivity to the neutron EDM over what is reported in the literature. The experiment has the potential to

- measure the magnitude of the neutron EDM or
- lower the current experimental limit by one to two orders of magnitude

Achieving these objectives will have major impact on the understanding of the physics of both weak and strong interactions.

The figure of merit for EDM experiments is proportional to the strength of the electric field multiplied by the square root of the number of neutrons and the time they are exposed to the electric field. This EDM experiment improves on all three of these quantities by taking advantage of the special properties of liquid helium (LHe). The UCN are produced in the LHe by employing the superthermal method where very high densities of UCN are produced in an experimental bottle by down-scattering cold neutrons from helium atoms, resulting in a UCN and a phonon. The LHe is a very good dielectric, permitting the application of a very high electric field to the measurement volume. The cryogenic temperatures will allow for long storage, and, thereby, measuring times of the UCN. This method is currently the only experimental approach being proposed in the U.S.

The experiment is based on the magnetic-resonance technique of rotating a magnetic dipole moment in a magnetic field. The nEDM experiment looks for a very small change in the precession rate of a neutron placed in a weak magnetic and a strong electric field when the electric field is oriented parallel or anti-parallel to the magnetic field. The experiment is extremely sensitive to small fluctuations of the external magnetic field that envelops the UCN. This problem is overcome by the addition of the only other species that can occupy the same volume as the UCN, which is ^{3}He and which has a magnetic moment very similar to that of the neutron but can have no EDM at the sensitivity of the experiment. The precession rate of the ^{3}He is measured by detecting their magnetization with superconducting quantum interference devices (SQUID). Thus, the ^{3}He provides a control measurement for the neutrons. The ^{3}He provides the extra benefit of measuring the precession rate of the neutrons through their highly spin-dependent capture cross section.

The apparatus to perform the measurement is illustrated in Fig. 1. It consists of a lower cryostat where the neutrons and ^{3}He will be studied and an upper cryostat where the polarized ^{3}He is prepared and the cryogenic environment is managed.

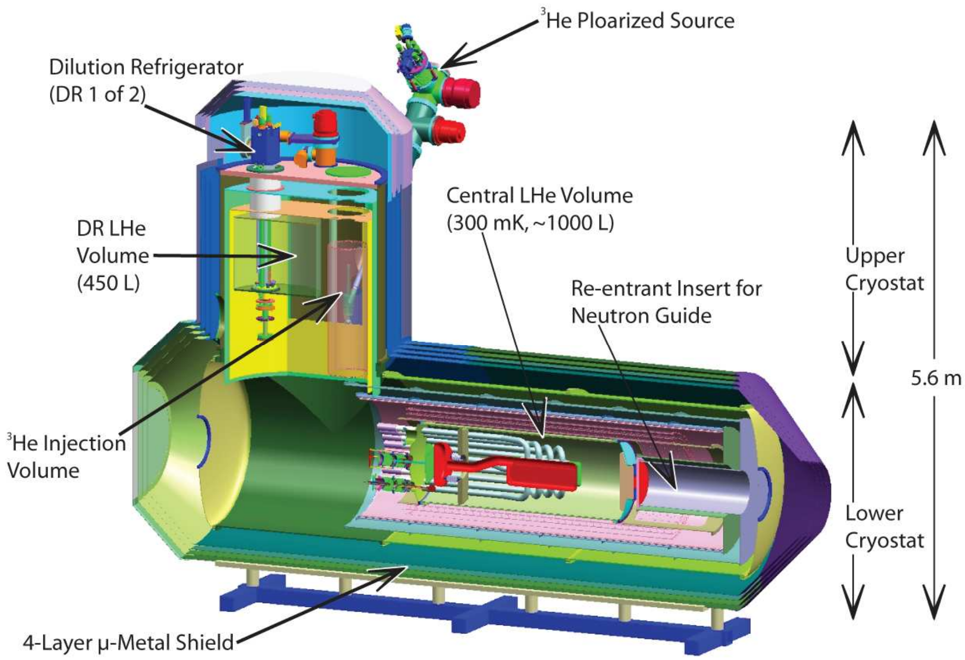

Figure 1. Schematic diagram of the nEDM apparatus.

3.2 Work Breakdown Structure

The nEDM Project has been organized into a Work Breakdown Structure (WBS). The WBS contains a complete definition of the project's scope and forms the basis for planning, executing and controlling project activities.

- Research and development (R&D) (WBS 1.1)
- Polarized neutron beam line and shielding (WBS 1.2)
- Cryostats, refrigerators, and related equipment (WBS 1.3)
- ^{3}He services (WBS 1.4)
- Magnets and magnetic shielding (WBS 1.5)
- Central detector systems (CDS) (WBS 1.6)
- Electronics, computers, simulations, and data analysis (WBS 1.7)
- Infrastructure (WBS 1.8)
- Assembly and commissioning (WBS 1.9)
- Project management and contingency (WBS 1.10)

R&D (WBS 1.1)

The R&D program is the experimental verification of the techniques proposed to execute the nEDM experiment. Pre-conceptual R&D efforts started in 1997 and R&D activities are scheduled to conclude at the end of calendar year 2007. Prior to CD-0, the experimental team obtained a number of important results including measurement of the

- ^{3}He diffusion coefficient in ^{4}He down to 0.45 K
- Kerr constant in LHe
- Temperature dependence of SQUID noise from 0.5-4.3 K

- Dielectric strength of LHe at 4.3 K
- Permeability of amorphous metals from 1-300 K
- Field uniformity of saddle shaped cosθ coils

During fiscal 2006, the team has also measured the
- S/N ratio for SQUIDs detecting unpolarized protons
- ^{3}He spin-relaxation time between 1.8-4.3 K
- After pulse response of LHe to neutrons and gamma rays
- A preliminary value for the storage time for neutrons in a deuterated polystyrene bottle

By the end of the R&D, the team will have
- Operated a prototype cryogenic valve built of the appropriate materials
- Operated a prototype purifier
- Operated a prototype ^{3}He injection system
- Operated SQUIDs around a high electric field
- Found operating parameters for the HV system at 0.5 K
- Tested a prototype of the light collection system
- Tested a ¼-scale prototype of the main magnetic field
- Measured the geometric phase effect in ^{3}He

The DOE R&D project funds are leveraged with LANL Laboratory Directed Reasearch and Development (LDRD) funds. Additional information on the R&D effort is located in the *WBS Descriptors* document and the *Risk-Based R&D Plan*.

Polarized Neutron Beam Line and Shielding (WBS 1.2)

This subsystem covers the design, procurement and commissioning of the neutron guides that transport the neutrons from the end of the FNPB section of the UCN beam line to the entrance to the experiment, a distance of ~15 m. The guides separate the beam into two polarization states and send each one into one of the two nEDM measurement cells. The polarization separation requires magnetized guide sections to either reflect or transmit each polarization state. These sections require a magnet to produce a holding field for the magnetic domains. Once polarized, the neutron in the guide must be surrounded by a coil to provide a holding field for the polarization. The holding field will be matched to the main field of the experiment. Radio-frequency spin flippers are required to set the states in each arm parallel to the ^{3}He.

Cryostats, Refrigerators, and Related Equipment **(WBS 1.3)**

This subsystem delivers the cryogenic vessel and all refrigeration to operate the experiment in the temperature range from 200-600 mK. The subsystem also includes all cryogenic links amongst the subsystems and overall management of the heat budget as well as coordination of cryogenic development throughout the project. Most ports, feedthroughs and pumping lines necessary to connect to the experimental apparatus between any two temperature regions, e.g. room temperature, 4 K and the operating temperature are included. The design, procurement, testing, and installation of the equipment is part of the subsystem, and the planning in this subsystem will be critical to the assembly of the full apparatus.

^{3}Helium Services (WBS 1.4)

The ^{3}He Services (He3S) Subsystem is responsible for the management and control of purified liquid ^{4}He and polarized ^{3}He during the measurement cycle. The bulk of this apparatus consists of custom-built, one-of-a-kind items. Special materials will be used that are nonmagnetic, nonsuperconducting, ^{3}He "friendly" and not readily activated by neutrons as appropriate to the application. The materials requirements and lack of off-the-shelf components imply that a large engineering effort will be required. These items will be separately tested to check the purification, polarized ^{3}He injection and holding, and pressurization functions. The valves that will control the state of the experiment and the interconnections between volumes require significant engineering during the R&D to achieve the required reliability. Subsequently, a final test of the performance of the full system will be carried out. Also included in the scope of this subsystem are mating of the atomic beam source to the injection region and the refurbishment and instrumentation of a bulk helium purifier based on the McClintock "heat flush" mechanism.

Magnets and Magnetic Shielding (WBS 1.5)

This WBS element includes the design, procurement, testing, and installation of the magnets and magnetic shields onto the apparatus. The entire experiment (both the upper and lower cryostat) will be enclosed within a cylindrical four-layer μ-metal magnetic shielding structure held at room temperature. The proposed shields are very large, with the largest cylinder having a diameter and length of ~8 ft and ~21 ft, respectively. Residual magnetic fields penetrating the four-layer conventional (μ-metal) magnetic shielding structure will be expelled by a cylindrical superconducting lead shield mounted in between the 4 K shield for the cryostat and the inner 4 K ferromagnetic shield. The magnets will produce the constant 10-mG field, the $\pi/2$ pulse, gradient fields, and dressing fields. Additional details are found in the *WBS Descriptors* book.

Central Detector Systems (WBS 1.6)

The CDS includes the
- measurement cells and the ^{3}He-valve bodies that are part of the measurement cell
- cintillation-light transport and detection system
- SQUID magnetometers
- beam stop
- HV electrodes, generating system, and monitoring system

The scope of this subsystem includes the design, procurement, and installation of the above subcomponents. Also, constructing appropriate apparatus to conduct tests of these subcomponents and performing the tests itself are also part of the scope of the subsystem.

Electronics, Computers, Simulations, and Data Analysis (WBS 1.7)

This WBS element comprises four work packages to
- develop a slow-controls system for the nEDM apparatus
- develop a data acquisition (DAQ) system for the nEDM experiment
- carry out simulations of all aspects of the experiment

- develop analysis codes to process the large amounts of data obtained over the multiyear duration of the experiment

Infrastructure (WBS 1.8)

The infrastructure of the nEDM Project is concerned with the integration of the nEDM experimental apparatus into the UCN experimental hall at the SNS facility at ORNL and the mechanical devices necessary to assemble and service it. This subsystem covers the services to the experimental equipment, such as electrical, plumbing and gas as well as the fabrication of mechanical platforms to allow for safe access to the experimental equipment. This section also includes designing and fabrication of jigs and fixtures for the experiment, which allow for the installation as well as maintenance of the equipment. The last task included is the procurement and installation of a counting house facility in the UCN experimental hall.

Integration and Commissioning (WBS 1.9)

The purpose of this element is to bring together the tested components from the other work packages (Cryostat, Insert, ^{3}He Components, Coil Package and Magnetic Shields, and DAQ) and assemble them together to form a complete apparatus.

Project Management and Support (WBS 1.10)

The subsystem provides the management and support functions required to integrate, manage and deliver the baseline performance outcomes for the nEDM Project. This subsystem includes the necessary National Environmental Protection Act (NEPA), communications, and reporting functions for the nEDM Project.

3.3 Technical Scope and Deliverables

The project, as described in this document, makes the assumption that DOE is the only Federal agency providing support for the fabrication of the project. Negotiations are underway regarding a possible contribution to the project from the National Science Foundation (NSF), which would transfer part of the DOE technical scope described below to the NSF and reduce the DOE total project cost (TPC). These agreements are expected to be in place prior to CD-2.

The technical scope of the project consists of the following activities or procurements:

- construction of the polarized neutron beamline and shielding for the experiment
- construction of the cryogenic vessel and all associated services
- construction of the
  - ^{3}He source and injection system
  - the helium purifier
  - all valves that control the state of the system
- construction of all required magnets and magnetic shields
- construction of the
  - measurement cells
  - high-voltage (HV) system

  - SQUID (superconducting quantum interference device) detectors
  - light-detection systems in the central region
- installation of all needed support services and production of assembly equipment
- development of all required electronics for both data acquisition and slow controls as well as computer systems for data acquisition and analysis
- assembly of the apparatus at the FNPB

3.4 Experiment Specifications

The principle specifications for measuring the performance of the nEDM experiment are given in Table 1 taken from the CDR. The minimal performance specifications are those that should be met following the first engineering run of the experiment, well after completion of the nEDM Project. The optimal performance specifications are needed to obtain the ultimate sensitivity. A set of supplementary specifications is available in the CDR. The object of the nEDM Project is to construct an apparatus that will meet these specifications at the end of engineering runs that will follow the project.

Table 1. The Principle Specifications for the nEDM Experiment[a]

Description	Minimal Performance	Optimal Performance
Operating Temperature (mK)	300–550	300–550
UCN Wall Loss Time (s)	200	2000
Capture Signal/Electron Background	0.5	50
^{3}He-Spin Relaxation Time (s)	200	30,000
^{3}He Polarization (%)	80	99
SQUID Noise ($\mu\phi_0$)/$\sqrt{Hz}$	20	1
Magnetic Field (B_0) Uniformity	2×10^{-3}	5×10^{-4}
Magnetic Gradient $\langle \delta B_x/\delta x \rangle_{vol}$ (μG/cm)	0.05	0.01
Electric Field (kV/cm)	25	50
UCN Production Rate (/cm^3/s)	0.08	0.3

[a] The minimal performance is the first goal of the collaboration and the optimal performance is needed to reach the ultimate sensitivity.

3.5 CD-4 Requirements

The attainment of these CD-4 requirements will demonstrate that all of the crucial functions of the apparatus work at a level where there is a reasonable probability that the scientific goals of the project will be reached.

The CD-4 deliverables needed to complete the nEDM Project are

Cryogenic vessel installed at ORNL

- Demonstrated to cool the central detector volume to 500 mK
- Operated with the magnet coil package and central insert in place

Magnet coil package installed at ORNL
- $\langle dB/dx \rangle / B_0 < 10^{-5}$/cm at 77 K achieved at Caltech

Four-layer magnetic shield in storage at ORNL
- Shielding factor of 10^{-4} achieved at Caltech

Central detector insert installed at ORNL but the following requirements met at LANL
- High voltage holds ≥ 5 kV/cm with a leakage current < 10 nA
- Mean number of photoelectrons from 750 keV of energy deposition is ≥ 4
- SQUID noise < 100 $\mu\Phi_0/\sqrt{\text{Hz}}$ in 10 Hz bandwidth that, based on independent tests, implies a S/N>1
- Neutron storage time in similar cell demonstrated to be >100 sec in an independent test

^{3}He services installed at ORNL but the following requirements met at LANL or Illinois
- Produces ≥ 10^{11}/cm^3 of ≥ 70%-polarized ^{3}He in the collection volume as seen with a SQUID
- Purifier reduces the ^{3}He concentration to less than 1 part in 10^{11}
- ^{3}He demonstrated to move between volumes with a time constant of 500 sec
- Valves shown to operate over 500 cycles

Neutron guides installed at ORNL except for the final two meters
- Flux out/MW ≥ 2×10^6 n/A/cm^2/s/MW @ 8.9 Å with a polarization ≥70%

3.6 Alternative Analysis

Without a nEDM experiment, the opportunity to play the leadership role in achieving the necessary measurements to better understand the space-time properties of the neutron (in support of NP's mission) will be lost. In addition, the optimal return of investment from the FNPB and the scientific benefits anticipated with its construction will not be realized. The alternatives of not realizing this compelling scientific opportunity or playing a minor role in existing efforts elsewhere in the world that do not have the capabilities of the nEDM at the FNPB are not very appealing.

The nEDM experiment is designed to the most sensitive search for the neutron EDM of any in the world and provides complementary information to many other tests of the Standard Model of electroweak interactions such as direct production of supersymmetric particles, rare muon processes, electron EDM experiments, g-2, etc. To achieve the sensitivity, the nEDM team made crucial design choices in order to optimize the figure of merit $E\sqrt{N}\tau$, where E is the electric field, N is the number of neutrons in the measurement cell and τ is the storage time.

The first choice was to do the experiment in a cryogenic environment of LHe, which improves all three of the components of the figure of merit. LHe allows for higher electric fields due to its dielectric properties and longer storage times due to the damping of loss mechanisms. LHe also allows for the highest production rates of ultra-cold neutrons (UCN) in the measurement cell via the superthermal process. *In situ* production eliminates the losses due to transporting the neutrons and the dilution factor from the production and transport volumes.

The second choice is the addition of polarized ^{3}He to the cells to serve as a co-magnetometer. Experience from previous neutron EDM experiments has shown that magnetic fluctuations produce non-statistical data that limited their sensitivity. External magnetometers measure field variations averaged over the entire cell. By having another species coexistent with the neutrons, the magnetic fluctuations are removed on scales of millimeters and seconds. The co-magnetometer exploits the good scientific practice of having a control measurement where there should be no effect.

The third choice was to include both SQUIDs and dressed spin coils. The two methods of measuring the EDM will provide redundant cross checks that will be invaluable in demonstrating that the results are correct. The additional cost was less than 2.5% of the cost of the project.

The fourth choice was to move the ^{3}He amongst the various volumes by diffusion. During the pre-conceptual phase, the team planned on mechanical displacements that would have generated heat in the cryogenic system. The conceptual design simplified the apparatus considerably by recognizing that the ^{3}He would move between volumes if the system provided the proper concentrations in matching volumes.

The location for the assembly has only recently become clear. The cryogenic expertise of the collaboration does not reside at ORNL. With ORNL agreeing to provide a cryogenic physicist to the project, construction of the apparatus at the site of the experiment, i.e. the FNPB UCN guide hall, will be the most efficient method. The entire plan described in this PPEP depends on ORNL providing this cryogenic physicist nearly full time during assembly of the nEDM Project. The drop-dead date is January 2009, but it is highly desirable for this physicist to work on the cryogenic design at its initiation, i.e. as early as possible.

The order of assembly of the apparatus has been resolved to be the central insert, the coil package, and the ^{3}He services. Delaying the integration of the coil package provides time for a low-field, low-temperature evaluation without delay to the project and without having to put the external magnetic shield around the cryogenic vessel prematurely, where it would be in the way and in danger of being damaged.

The justification for the larger FNPB UCN guide hall has become stronger as the project has planned the assembly of the conventional magnetic shield around the cryostat. If nEDM is restricted to the original guide hall, there is an increased risk of schedule delays while workers try to figure out how to move these bulky objects into place in quite cramped quarters.

The criteria for project completion have been studied by a team consisting of Paul Huffman (NSCU and nEDM Technical Coordinator), Vince Cianciolo (ORNL Operations Manager), Geoff Greene (FNPB CPM), and Martin Cooper (nEDM CPM). The conclusion is that the CD-4 requirements presented in Section 3.5 are well matched to concluding the project when the ^{3}He services have been installed in the experiment. These requirements are a reasonable place to transfer to operations and when satisfied will provide DOE with a reasonable assurance that the nEDM Project has delivered a detector that can meet the scientific goals of the experiment.

4. Management Systems - Organization and Responsibilities

A schematic representation of the management arrangement is shown in Figure 2. The solid lines represent the lines of authority from the Contractor Project Manager up through the DOE Program Manager, and the dotted lines indicate where communication, coordination, and support are required.

4.1 Department of Energy

Within the DOE-SC, the Office of Nuclear Physics (SC-26) has overall DOE responsibility for the nEDM Project.

The Acquisition Executive is Dennis Kovar, Associate Director of the Office of Science for Nuclear Physics (SC-26). As such, for the nEDM Project, he has full responsibility for project planning and execution and for establishing broad policies and requirements for achieving project goals. Specific responsibilities for the nEDM Project include

- chairing the ESAAB (Energy Systems Acquisition Advisory Board) equivalent board,
- approving critical decisions and level-1 baseline changes,
- approving the Project Execution Plan,
- delegating approval authority for Level-2 baseline changes to the Federal Project Director,
- conducting quarterly project reviews
- ensuring that the Independent Project Reviews are conducted

The Federal nEDM Program Manager is Jehanne Simon-Gillo. The Office of Nuclear Physics (SC-26) is responsible for planning, constructing, and operating scientific instrumentation to provide special scientific and research capabilities to serve the needs of U.S. universities, industry, and private and federal laboratories. Within NP, the Facilities and Project Management Division (SC-26.2) has direct responsibility for providing funding, and programmatic guidance to the nEDM Project. The nEDM Program Manager, in SC-26.2, is the primary point of contact with the following responsibilities

- oversees development of project definition, scope, and budget
- prepares, defends and provides project budget with support from the field organizations
- functions as DOE HQ's point-of-contact for project matters
- oversees project progress and helps organize reviews as necessary
- ensures ESH&Q requirements are implemented by the project
- coordinates with other SC staff offices, HQ program offices, and the Office of Project Assessment (OPA) as needed to execute the project
- controls changes to project baselines in accordance with this PPEP

The assigned Federal Project Director is Eugene Colton at the DOE/NNSA Los Alamos Site Office (LASO). The Federal Project Director responsibilities include

- ensuring that the contractor designs and constructs a major item of equipment that meets mission requirements
- providing day-to-day oversight of the project and providing direction to ensure its timely execution
- functioning as the DOE/NNSA field point of contact for the nEDM Project

- leading and managing all Integrated Project Team (IPT) matters requiring coordination within LASO and ORO – the DOE/NNSA LASO and the DOE ORO (Oak Ridge Site Office) will need to maintain good communications, efficient administrative support and contractor accountability for the nEDM Project to succeed
- maintaining effective communications among SC-NP, LASO, and the nEDM Project
- monitoring, reviewing, evaluating, and reporting on the performance of the nEDM Project against established technical-, cost- and schedule-performance baselines
- participating in Project Reviews conducted by the nEDM Project and by DOE HQ
- ensuring that the project complies with applicable environmental, safety, security, and health requirements
- issuing Project Directives to authorize work within funding levels provided in approved Financial Plan Changes
- authorizing use of nEDM Project contingency in accordance with the levels described in this PPEP
- submitting key nEDM Project documents to SC-NP for concurrence/approval
- reporting progress and update nEDM Project data in the DOE Project Assessment and Reporting System (PARS)
- maintaining cognizance of nEDM Project activities, anticipating potential problems, and taking corrective actions to minimize project impacts
- controlling changes within established authority to nEDM Project baselines and seeking DOE HQ approval for changes beyond the Federal Project Director's authority
- performing other functions described for the Federal Project Director in the Project Management for the Acquisition of Capital Assets Manual (DOE M 413.3-1)

4.2 LANL Physics Division Leader

The LANL Physics Division Leader is Jack Shlachter. Funding for the nEDM Project will be directed through the LANL Physics Division. Thus, LANL line management will have ultimate fiscal and management responsibility for the construction of the nEDM Project. The CPM, Martin Cooper, reports to the LANL Physics Division Leader.

4.3 nEDM Contractor Project Manager

The nEDM Contractor Project Manager is Martin Cooper. The nEDM CPM will implement the nEDM Project through the managing and operating (M&O) contractor for LANL, currently the Los Alamos National Security, LLC (LANS), which will be responsible for overall project coordination, execution, and eventual equipment operation. The nEDM CPM will report to the LANL Physics Division Leader. The nEDM CPM will be responsible for the overall planning and successful execution of the nEDM Project, including

- executive-level management of the design, construction and transition to operations of the nEDM Project equipment to ensure all mission requirements are fulfilled in a safe, cost-efficient and environmentally responsible manner
- exercising full financial authority and accountability as delegated by DOE and the LANS, LLC, to develop budgets and control nEDM Project work within approved baselines, and control

changes to approved baselines in accordance with established configuration-management procedures

- manage and direct procurements within the authority delegated by DOE and the LANS, LLC, including the authority to execute and deliver contracts, agreements, teaming agreements, purchase orders, assignments, and instruments and documents of any kind relating to the acquisition, sale, or disposition of products, services, materials, supplies, and equipment relating to or necessary and desirable for the completion of the nEDM Project
- overall responsibility to recruit and manage the human resources necessary to complete the nEDM Project and ensure an effective transition to operations, including the overall responsibility for managing the human-resources systems within the authority delegated by DOE
- maintaining relationships with the international scientific communities which are designing and pursuing similar neutron experiments, to keep informed of current progress and developments of potential significance to the nEDM
- management of day-to-day execution in accordance with requirements, procedures, and standards, as set forth in the LANL M&O contract
- full integration with the collaboration and ORNL to ensure that all interfaces are planned and executed
- ensuring safety and security are studied and integrated into the design and construction

4.4 nEDM Integrated Project Team

The nEDM Project proposes an IPT that consists of core members who are the Federal Project Director, the nEDM CPM, and the DOE Program Manager. The proposed IPT is led and organized by the Federal Project Director. The IPT will additionally consist of the necessary technical and support personnel responsible for the early planning and description of the nEDM Project (see Table 2). The IPT may also include other essential members of the nEDM Project organization and is shown in Figure 2.

4.5 Interfaces

Before CD-2, Memoranda of Understanding (MOU) will be generated between LANL and the other institutions collaborating on the nEDM Project.

Before CD-2, agreement on the roles and responsibilities of the DOE and the NSF will need to be established.

Table 2. nEDM Integrated Project Team

Functional Area	Name	Location/Organization
Federal Project Director	Eugene Colton	Los Alamos/LASO
Program Manager	Jehanne Simon-Gillo	Germantown/SC
Science Program Manager	Gene Henry	Germantown/SC
Industrial Safety & Health	John Pearson	Oak Ridge/ORO
Contract/Acquisition Support	Caroline Crooks	Los Alamos/LASO
NEPA Support	Mark Belvin	Oak Ridge/ORO
Quality Assurance	Dave Rosine	Oak Ridge/ORO
Fire Protection	Patrick Smith	Oak Ridge/ORO
Site Representative	David Arakawa	Oak Ridge/ORO
LANL Contractor Project Manager	Martin Cooper	Los Alamos/P-25
LANL Chief Engineer	Jan Boissevain	Los Alamos/P-25
LANL ESSH Lead	P-25 Safety Officer	Los Alamos/P-25
Technical Coordinator	Paul Huffman	NCSU/ORNL
ORNL Operations Manager	Vince Cianciolo	Oak Ridge/ORNL
FNPB Scientific Director	Geoff Greene	Oak Ridge/ORNL

4.6 nEDM Collaboration Internal Structure

The project office consists of

- The Contractor Project Manager (CPM), Martin Cooper, whose duties are described above
- The two scientific co-spokespersons, Martin Cooper and Steve Lamoreaux, represent the scientific interests of the experiment both internally and externally
- The Project Controls Analyst (PCA), Kim Selvage, manages the MS Project schedule file and the associated work packages as well as other project documentation
- The Chief Engineer, Jan Boissevain, coordinates the engineering of the many engineers who are at dispersed sites around the collaboration and is also responsible for drawing and version control
- The Technical Coordinator, Paul Huffman, oversees the technical efforts across the subsystems with special emphasis on cryogenic best practices
- The ORNL Operations Officer/ESH Responsible, Vince Cianciolo, interfaces the nEDM project to ORNL and the FNPB Project as well as plans and organizes activities at the FNPB

Most of the salaries of these individual come from the operations budgets of their home institutions. The charges to the nEDM Project are the CPM (initially 30% FTE but decreasing after assembly begins), the PCA (initially 40% FTE but decreasing after assembly begins) and the Chief Engineer (50% FTE but decreasing after CD-3b).

The Executive Committee is an advisory committee to the CPM and the co-spokespersons on matters affecting the project and the collaboration. The committee consists of the CPM (chair), the co-spokespersons, the technical coordinator, the ORNL operations officer, and representatives from four universities in the collaboration. They provide advice on issues the CPM chooses to bring before them regarding the project as well as a wide variety of technical and administrative advice regarding the collaboration. Some examples of their actions are the first phase of approval for new institutions to join the collaboration and the establishment of publication policies.

The Subsystem Managers will execute the construction of their parts of the project. They have been intimately involved in the project planning, developing both the work packages and the project schedule that have led to the cost estimates for the project. They will be responsible for organizing the construction of their subsystems through work packages distributed to the collaboration. They will be responsible for reporting progress to the CPM and the PCA on a periodic basis.

4.7 nEDM Collaboration

The collaboration currently consists of the following institutions:

Institution	Funding	Subsystems (Work Packages)
• Arizona State University	NSF	Magnets
• University of California at Berkeley	NSF*	Central Detector (HV)
• California Institute of Technology	NSF*	Magnets
• Duke University	DOE	^{3}He (Injection)
• Hahn-Meitner Institut	Germany	Neutrons
• Indiana University	NSF*	Central Detector (SQUIDS, HV), Neutrons
• University of Illinois-Urbana-Champaign	NSF*	^{3}He
• University of Kentucky	DOE	Neutrons
• Los Alamos National Laboratory	DOE	Central Detector, Infrastructure, Project
• Massachusetts Institute of Technology	DOE	TBD
• North Carolina State University	DOE	Cryogenics, Electronics, Assembly
• Oak Ridge National Laboratory	DOE	Cryogenics, Assembly
• Simon-Frasier University	Canada	^{3}He
• University of Tennessee	DOE	Neutrons
• Yale University	NSF	Central Detector

The US institutions have their nEDM funding source identified. Their commitments to the construction of the nEDM subsystems are also identified. The institutions whose base funding come from the NSF but who have received DOE R&D funds are denoted with a *. New institutions are still joining the collaboration and will provide a welcome enhancement to the workforce.

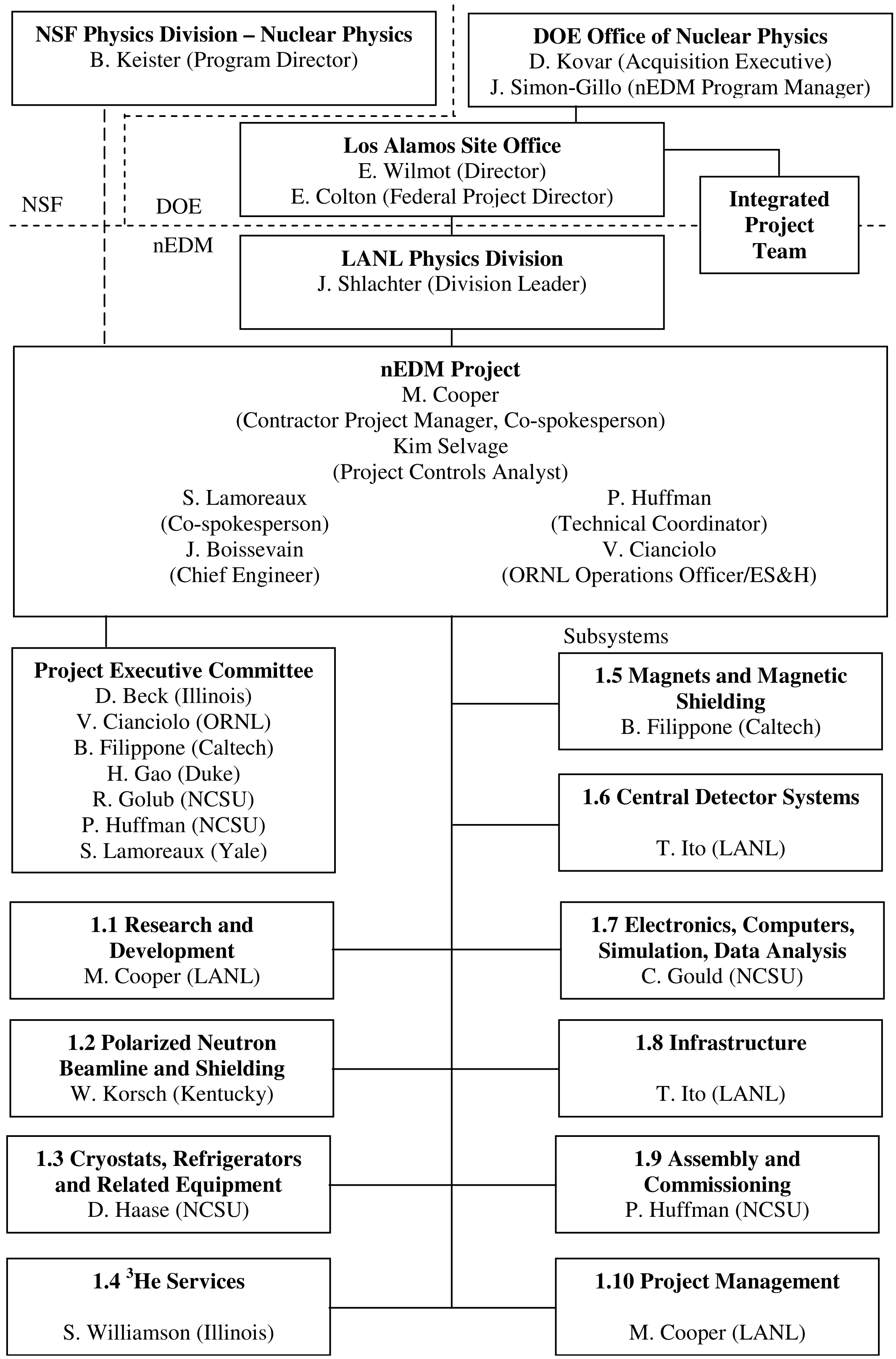

Figure 2. nEDM Project organization

5. Schedule and Cost Scope

The LANS, LLC is the M&O contractor for LANL. As such, the nEDM Project will be managed through LANS, and contracts with the universities as appropriate. The nEDM Project will make use of existing staff and facilities from the collaboration, and the FPD, working with DOE-ORO, will ensure the installation is carefully coordinated with other research activities at ORNL.

Project activities will be accomplished to the extent feasible using fixed-priced subcontractors selected on the basis of best value, price, and other factors. Details are provided in the *nEDM Acquisition Strategy*.

Design and equipment-fabrication activities will be accomplished to the greatest extent possible by fixed-price commercially provided services, fabrication services, and specialty engineering services. Where design or equipment-fabrication activities are not commercially available, or not practical due to schedule constraints or technology-transfer limitations, the nEDM Project will construct the design using the best available internal resources or resources of other national laboratories and universities.

The participation of females, minorities, and small/disadvantaged businesses (SDB) in the execution of the nEDM Project will be encouraged..

5.1 Contingency Analysis

The project budget includes contingency as an allowance for uncertainties, omissions and risks. The overall project contingency was calculated by estimating the contingency contribution from each WBS element. Each contribution was based on an assessment of the technical, cost and schedule risk with a weight that reflects the type of cost (labor or material). These individual contributions are summed to give the project contingency. Although contingency is calculated at the subsystem level, it is not specifically assigned to a particular subsystem but is held at the total project level.

In the project, contingency is calculated using a deterministic approach that mimics from the one used by the FNPB. This same procedure is commonly used in high-energy-detector construction projects and other projects of a similar scale.

The procedure for contingency calculation begins with a base cost estimate. The base cost estimate is the estimated cost of doing things correctly the first time unless past experience has shown that more than one effort will probably be needed, e.g. in the commissioning of cryogenic equipment. Thus contingency is not included in the base cost. Contingency is calculated as a percentage of the base cost estimate. The cost contingency percentage for a particular WBS activity is calculated using the following procedure:

1. Compare the state of the activity with Table 3 to determine risk factors
2. Compare the potential risk within an activity with Table 4 to determine the appropriate weighting factors
3. Multiply the individual risk factors by the corresponding weighting factors, and then sum them to determine the composite contingency percentage

4. Calculate the dollar amount of contingency for an individual activity by multiplying the base cost by the calculated contingency.

Two slight modifications were made to the process. One was to account for commodity futures like the price of nickel and the value of the dollar through application of the Black-Scholes equation, whose origin is economic theory. The result from the formula applied for three years into the future was to add 15% to the contingency beyond the tabular result. The second modification was to assign a risk factor of 4 to the cost piece of the contingency for those items where the R&D might dramatically modify the reference design.

The above process was executed by the individual subsystem managers on their subsystems. Consistency amongst the subsystems was achieved by working a variety of examples in a workshop held for the subsystem managers and by dialogue between the CPM and the subsystem managers. The subsystem managers also produced subsystem project schedules that included durations for each activity and logical links between activities. Horizontal integration amongst the subsystems was initiated at a workshop for the subsystem managers and completed through a dialogue with the CPM.

Contingency percentages for individual elements in this project vary from a low of 9 % to a high of 78%. The overall project contingency percentage is 33%. The highest activity contingencies reflect the risk associated with systems where R&D is ongoing and expected to influence the design. The percentage contingency is expected to decline between now and CD-2 when there will be a more refined engineering design that allows for better estimating, e.g. from a larger fraction of items priced from vendor quotes.

Schedule contingency is estimated by multiplying the estimated duration of each activity by the components for technical and schedule risk times their respective weighting factors and then summing to get the schedule contingency for that activity. The schedule durations include the schedule contingency on each activity. The milestones are determined from the resulting schedule. The project schedule contingency is calculated by comparing the completion date with and without schedule contingency included. The overall-project schedule contingency is 304 days or 10 months.

Internally, the project will be managed without the inclusion of schedule contingency to an earliest finish for each activity. The accumulated schedule contingency will be managed on a project-wide basis from the project office in analogy with the management of cost contingency.

Table 3. Technical, cost and schedule risk factors

Technical	Cost	Schedule	Risk Factor
Existing design and off-the-shelf hardware	Off-the-shelf or catalog item		1%
Minor modifications to an existing design	Vendor quote from established drawings	No schedule impact on any other item	2%
Extensive modifications to an existing design	Vendor quote with some design sketches		3%
New design, nothing exotic	In-house estimate based on previous similar experience	Delays completion of non-critical path subsystem item	4%
New design, different from established designs or existing technology	In-house estimate for item with minimal experience but related to existing capabilities		6%
New design, requires some R&D but does not advance the state-of-the-art	In-house estimate for item with minimal experience and minimal in-house capability	Delays completion of critical path subsystem item	8%
New design, development of new technology which advances the state-of-the-art	Top –down estimate from analogous programs		10%
New design, far beyond the current state-of-the-art	Engineering judgment		15%

Table 4. Technical, cost and schedule risk weights

Technical	Cost	Schedule	Risk Weight
———	Material cost or labor rate	Same for all	1
Design or Manufacturing	Material cost and labor rate		2
Design and manufacturing			4

5.2 Control Milestones

The nEDM Project preliminary baseline schedule is defined by the Level 1 milestones shown in Table 5. The project was initiated at CD-0, on Q1 2006 and is scheduled to complete on Q4 2013. A preliminary level 2 milestone schedule for the construction of the nEDM experimental apparatus are shown in Table 6. These tables assume a funding profile as described in Table 10.

The CPM has identified three long-lead time items, the main cryostat, the He liquefier and the second dilution refrigerator, to be placed on a rapid procurement path. These items must be purchased early to be ready for installation when the nEDM Project receives beneficial occupancy of the UCN guide hall from the FNPB Project. The early procurement keeps the main cryostat off the critical path and leads to an earlier project completion date. The combined cost of these three items is roughly $2.4M.

The need for early procurement has led to the tailoring of the level-1 milestones in Table 5. The CD-3a approval is sought simultaneously with CD-2 approval. At the time of CD-2 approval, the R&D will be completed and incorporated into the baseline design. The CPM will then be ready to commit to these three major procurements. The liquefier is a catalogue item; the dilution refrigerator is a commercial item based on well tested designs; and the cryostat design is being pushed as an organizing structure for the preliminary design. Each will be a fixed price contract.

Figure 3 illustrates the critical path for the nEDM Project. Initially it proceeds through the R&D necessary to establish technical feasibility. Next, it passes through a period in preparation for the CD-2, 3a review while the results of the R&D are being incorporated into the project plan. Prior to the start of construction, the final engineering is finished before the CD-3b review. The critical path then bifurcates into two paths, one where the coil package is constructed and tested with the 4-layer magnetic shield and one where the central detector insert is constructed and commissioned in the main cryostat. The assembly continues until the ^{3}He services are installed in the main cryostat. Finally, CD-4 approval ends the nEDM Project. Figure 4 shows the time period spanned by each subsystem.

Table 5. MIE Level 1 Milestones

Level	Major Milestone Events	Completion Date
1	CD-0 – Approve Mission Need	Qtr 1, FY 2006
1	CD-1 – Approve Alternative Selection and Cost Range	Qtr 2, FY 2007
1	CD-2 – Approve Performance Baseline	Qtr 3, FY 2008
1	CD-3a – Approve Start of Long-lead Procurement	Qtr 3, FY 2008
1	CD-3b – Approve Start of Construction	Qtr 1, FY 2009
1	CD-4 – Approve Start of Operations	Qtr 3, FY 2013

Table 6. MIE Level 2 Milestones

Level	Major Milestone Events	Completion Date
2	R&D Complete	Qtr 1, FY 2007
2	Cryostat Order Placed	Qtr 4, FY 2008
2	Test Cryostat Available	Qtr 2, FY 2009
2	Cryogenic Installation Starts	Qtr 4, FY 2009
2	Conventional Shield Delivered	Qtr 1, FY 2010
2	Main Cryostat Operational	Qtr. 3, FY 2010
2	Beam Line Commissioned	Qtr. 3, FY 2010
2	Insert Full System Test Passed	Qtr. 3, FY 2011
2	Coil Package Tested	Qtr. 2, FY 2012
2	Insert Commissioned	Qtr. 2, FY 2012
2	^{3}He Full System Test Passed	Qtr. 4, FY 2012
2	Coil Package Commissioned	Qtr. 1, FY 2013
2	^{3}He Components Assembled in Main Cryostat	Qtr 3, FY 2013

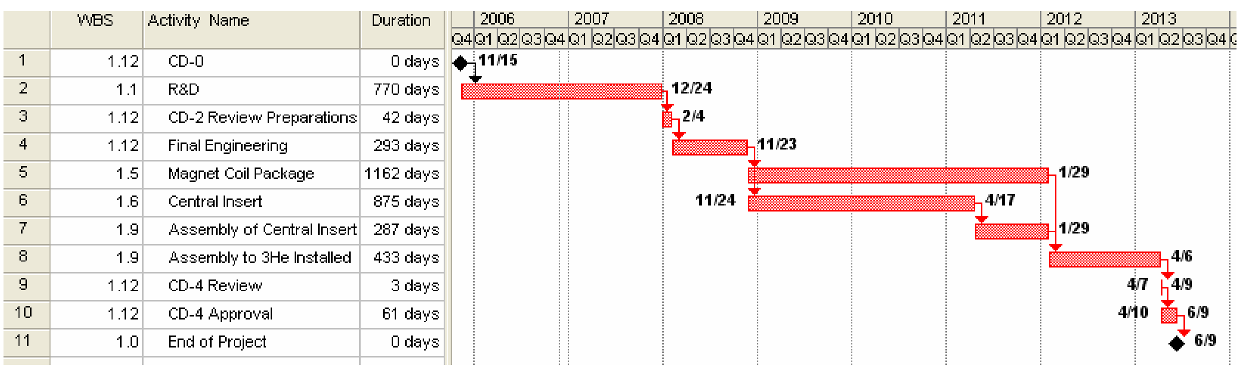

Figure 3. The critical path for the nEDM Project

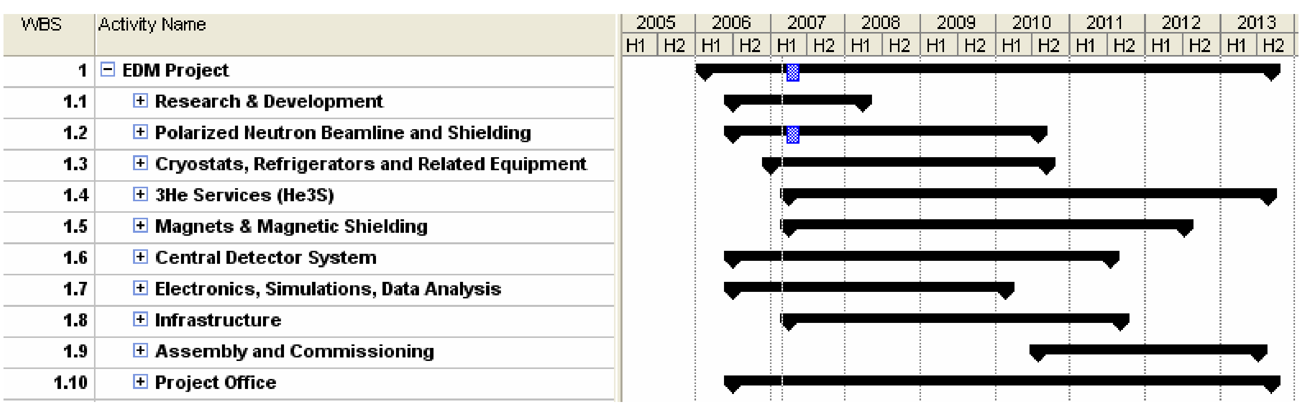

Figure 4. The time spanned by each subsystem

5.3 Escalation

The costs for the nEDM project were estimated in FY'06 dollars and escalated to actual year dollars using the escalation indices recommended in the "DOE FY 2008 Field Budget Call" and by the Office of the Chief Financial Officer at LANL. Searching for an alternate set of indices did not reveal a more valid approach. Separate escalation indices and multiplier factors were used for labor and for procurements; they are given in Table 7. The annual costs per subsystem for labor and procurements were obtained from the "time scaled data" feature of MS Project.

Table 7. Escalation Indices used for the nEDM Project

	FY'06	FY'07	FY'08	FY'09	FY'10	FY'11	FY'12	FY'13
Labor Rate	0.0%	4.2%	4.8%	4.8%	4.8%	4.8%	4.8%	4.8%
Labor Factor	1.000	1.042	1.092	1.144	1.199	1.257	1.317	1.380
Procurement Rate	0.0%	2.1%	2.2%	2.2%	2.2%	2.2%	2.2%	2.2%
Procurement Factor	1.000	1.021	1.043	1.066	1.090	1.114	1.138	1.163

5.4 Project Cost

The CD-0 preliminary cost range was between $12M–18.3M. The CD-1 cost range is between $17.6-19.8M. The preliminary estimate for the TPC at CD-1 is $18.43M in Actual Year Dollars, with an average contingency value of 33%.

The lower end of the range is arrived at by assuming that 20% of the $4.2M of contingency will not be spent. The upper end is arrived at by assuming that no more than $5M in funding will be available in any given fiscal year, which adds $0.67M in escalation and project office costs resulting from a two year delay in project completion as well as another $0.70M for options that change the definition of completion of the project to be at the time commissioning ends.

The estimated budget of $18.43 M includes all DOE base costs developed "bottoms-up" from the lowest appropriate WBS level. The breakdown of the TPC by subsystems and other components is illustrated in Tables 8a and 8b. The base cost is $12.7M. The TPC is the base cost plus $4.2M in contingency and $1.5M in escalation. The percentage contingency is highest at 42% for the riskiest subsystems: ^{3}He Services, Magnets and Magnetic Shielding, Central Detector Systems, and Assembly and Commissioning. The average technical contingency is 35% and is the value calculated by deleting the R&D and project office subsysems. Table 9 contains more details to WBS level 3 in units of $k.

Table 10 and Figure 5 show the annual budget costs for the nEDM project as well as the CD-0 DOE guidance. The table breaks out the OPC into R&D and CDR preparation. It also divides the TEC into design, long lead procurements and construction. With the end of the nEDM Project scheduled to coincide with the installation of the ^{3}He services, there is no commissioning or preops planned during the project.

The funding spike in FY'09 is likely to prove problematic. The consequences of putting a $5M cap on budget authority for any one year is a two year delay in project completion and a $0.67M increase in the TPC due to increased escalation and project office costs. It is assumed at CD-1 that the only Federal agency supporting the project fabrication is DOE. The role of NSF will need to be articulated prior to CD-2.

The $18.43M TPC is divided as $0.66M OPC and $17.77M TEC. The OPC will pay for the R&D and for the project office prior to CD-1 approval. Commissioning of the apparatus will take place after the end of the nEDM Project.

Table 8a. Cost Summary

WBS	Subsystem	Labor Estimate	ODC Estimate	Major Purchases	Base Subtotal
1.01	Research & Development	$ 43,106	$ 270,909	$ 19,386	$ 333,401
1.02	Polarized Neuron Beam Line & Shield	$ 193,484	$ 162,100	$ 1,294,687	$ 1,650,271
1.03	Cryostats, Refrigerators	$ 783,037	$ 808,840	$ 2,149,000	$ 3,740,877
1.04	3He Systems	$ 478,227	$ 526,021	$ 100,000	$ 1,104,248
1.05	Magnets & Magnetic Shielding	$ 341,299	$ 390,705	$ 1,149,160	$ 1,881,164
1.06	Central Detector System	$ 320,245	$ 317,627	$ 637,550	$ 1,275,422
1.07	Electronics, Computers, Simulations	$ 117,477	$ 97,090	$ 229,000	$ 443,567
1.08	Infrastructure	$ 276,084	$ 239,530	$ 246,320	$ 761,934
1.09	Assembly & Commissioning	$ 239,038	$ 27,740	$ -	$ 266,778
1.10	Project Management	$ 1,235,634	$ 29,575	$ -	$ 1,265,209
Grand Total		$ 4,027,631	$ 2,870,137	$ 5,825,103	$ 12,722,871

Table 8b. Cost summary

WBS	Subsystem	Base Subtotal	Contingency	TPC w/o Escalation	Escalation	TPC	% Contingency
1.01	Research & Development	$ 333,401	$ 116,690	$ 450,092	$ 7,667	$ 457,759	35%
1.02	Polarized Neuron Beam Line & Shield	$ 1,650,271	$ 563,465	$ 2,213,736	$ 160,012	$ 2,373,748	34%
1.03	Cryostats, Refrigerators	$ 3,740,877	$ 1,114,651	$ 4,855,529	$ 362,221	$ 5,217,750	30%
1.04	3He Systems	$ 1,104,248	$ 463,843	$ 1,568,091	$ 174,992	$ 1,743,083	42%
1.05	Magnets & Magnetic Shielding	$ 1,881,164	$ 788,770	$ 2,669,934	$ 230,865	$ 2,900,799	42%
1.06	Central Detector System	$ 1,275,422	$ 540,849	$ 1,816,271	$ 162,107	$ 1,978,378	42%
1.07	Electronics, Computers, Simulations	$ 443,567	$ 132,544	$ 576,111	$ 35,429	$ 611,540	30%
1.08	Infrastructure	$ 761,934	$ 198,633	$ 960,568	$ 78,268	$ 1,038,836	26%
1.09	Assembly & Commissioning	$ 266,778	$ 112,686	$ 379,464	$ 112,465	$ 491,929	42%
1.10	Project Management	$ 1,265,209	$ 126,521	$ 1,391,730	$ 221,611	$ 1,613,341	10%
Grand Total		$12,722,871	$ 4,158,653	$16,881,524	$ 1,545,637	$ 18,427,161	33%
Technical Contingency			$ 3,915,441	$15,039,702			35%

Table 9. nEDM costs to WBS level 3

1	**nEDM Project**				
1.1	**Research & Development**	**$450**	1.5.7	3He Spin-Holding Coil	$101
1.1.1	Critcal R&D	$138	1.5.8	3He Spin-Holding Coil Ferromagnetic Shield	$63
1.1.2	Critical R&D prior to CD-2b	$312	1.5.9	Field Monitors	$115
1.2	**Polarized Neutron Beamline and Shielding**	**$2,214**	**1.6**	**Central Detector System**	**$1,816**
1.2.1	Modeling	$8	1.6.1	Preliminary design coordination	$2
1.2.2	Design	$125	1.6.2	HV system	$342
1.2.3	Procurement	$1,986	1.6.3	Kerr Rotation HV Monitor	$146
1.2.4	Installation	$95	1.6.4	Measurement cells	$154
1.3	**Cryostats, Refrigerators and Related Equipment**	**$4,856**	1.6.5	SQUID System	$426
1.3.1	External Cryogenic Vessel , Intermediate and 4 K Shields	$933	1.6.6	Light system	$246
1.3.2	Helium Electrical Insulation Volume	$385	1.6.7	Insert end cap	$147
1.3.3	Refrigerators	$2,612	1.6.8	V1 Valve	$53
1.3.4	Cryovessel Sensors and Controls (WP)	$190	1.6.9	Beam stop and neutron shield	$34
1.3.5	Cryovessel Assembly, Testing and Operation Infrastructure	$558	1.6.10	test apparatus	$95
1.3.6	Assembly and Testing of Cryovessel and Refrigerators	$177	1.6.11	Central detector system integration and tests	$172
1.4	**3He Services (He3S)**	**$1,568**	**1.7**	**Electronics, Simulations, Data Analysis**	**$576**
1.4.1	3He Atomic Beam Source (ABS)	$22	1.7.1	Slow controls	$445
1.4.2	ABS Interface	$67	1.7.2	Data Acquisition System	$131
1.4.3	Polarized 3He Collection System	$175	**1.8**	**Infrastructure**	**$961**
1.4.4	3He Injection Test	$64	1.8.1	Platforms	$178
1.4.5	Purifier	$188	1.8.2	Electrical Plant	$136
1.4.6	Purifier Volume Displacement	$48	1.8.3	Plumbing	$150
1.4.7	Purifier/Valve Test	$65	1.8.5	Mechanical Supports	$407
1.4.8	Pressurizer	$44	1.8.6	Counting House	$89
1.4.9	Pressurizer/Valve Test	$40	**1.9**	**Assembly and Commissioning**	**$379**
1.4.10	Valves	$386	1.9.1	Coil Package Assembly/Commissioning at ORNL	$82
1.4.11	Interconnect Plumbing	$113	1.9.2	Insert Assembly/Commissioning at ORNL	$224
1.4.12	He3S (Full Subsystem) Test	$159	1.9.3	3He Component Assembly/Commissioning at ORNL	$74
1.4.13	He3S Installation in Upper Cryostat	$101	**1.10**	**Project Office**	**$1,392**
1.4.14	McClintock Purifier (Bulk Purified 4He)	$96	1.10.1	FY'06	$32
1.5	**Magnets & Magnetic Shielding**	**$2,670**	1.10.2	FY'07	$282
1.5.1	Four-Layer Conventional Shield	$1,453	1.10.3	FY'08	$262
1.5.2	Superconducting Shield	$83	1.10.4	FY'09	$262
1.5.3	Constant Field Coil Ferromagnetic Shield	$131	1.10.5	FY'10	$250
1.5.4	B0 Field Coil and Gradient Field Coils	$369	1.10.6	FY'11	$117
1.5.5	pi/2 Coil	$117	1.10.7	FY'12	$112
1.5.6	Dressed Spin Coils	$239	1.10.8	FY'13	$76
				Escalation	**$1,546**
				Total	**$18,428**

Table 10. Estimated Funding

	FY'06	FY'07	FY'08	FY'09	FY'10	FY'11	FY'12	FY'13	Total
R&D	$150	$300							$450
CDR	$50	$200							$250
Design		$800	$500	$200					$1,500
LL Procurement			$2,400						$2,400
Construction		$300		$9,900	$2,200	$600	$550	$300	$13,850
Preops									
Total	$200	$1,600	$2,900	$10,100	$2,200	$600	$550	$300	$18,450
DOE CD-0 Guidance	$200	$1,300	$3,000	$4,950	$5,000	$3,000	$850		$18,300

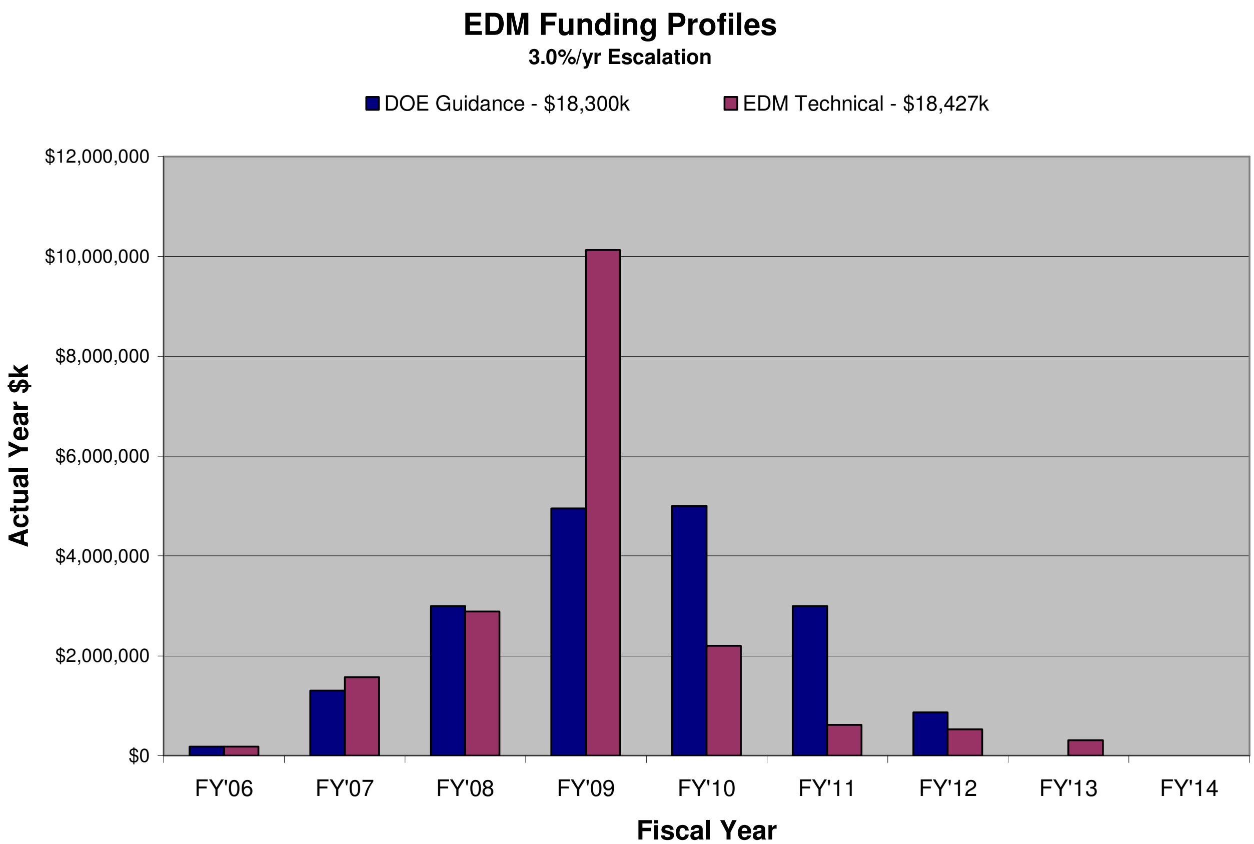

Figure 5**.** Funding profile for the nEDM project contrasted to the CD-0 guidance from DOE

5.5 Life Cycle Cost

The nEDM Project life-cycle cost reflects the TPC for design and construction, operation for the 5-year design life, and eventual decommissioning is estimated to be $20.18M. The breakout of this cost is the TPC of the project of $18.43M, an estimated operating cost of $0.25M/yr for a five-year total of $1.25M, and $0.5M D&D cost.

The operating costs do not include any costs for scientific staff to run the experiment, but rather are limited to technician and engineer salaries as well as materials and services. The breakdown of the $250k/year is $100k for a ½-FTE technician from ORNL, $50k for expendables like cryogens and $100k for necessary repairs or upgrades. The CPM assumes that these funds will be managed by ORNL as part of the operating costs of the FNPB. In conversations with ORNL, we have also noted the crucial need for ½-FTE of an on-site cryogenic physicist throughout the operational period, but that cost is not included in the life cycle cost because this individual will be one of many scientists participating in the data collection.

The D&D cost is based on the recent decommissioning of another experiment of similar complexity at LANL. The MEGA magnet was dismantled by Jefferson National Laboratory (JLab), leaving its site ready for other uses. The majority of the D&D costs were for JLab technicians. Small costs for the waste stream and radiation technicians were included.

6. Project Change Control

6.1 Change Control

An essential element of project-management systems is the control of changes to the project baselines and the implementation approach. The Project Controls Analyst will be responsible for administrative operation and coordination of the overall baseline change-control system in support of all nEDM Project participants, including processing all nEDM Project change requests (PCRs). This process will begin upon receipt of a draft PCR from the responsible Subsystem Manager and continue through various reviews to the issue and distribution of approved PCRs or baseline change proposals (BCPs), which require DOE review and approval.

The Project Controls Analyst will be responsible for implementing approved cost/budget and schedule/milestone baseline changes to the official nEDM Project baseline documents and files. Authorized baseline changes will be incorporated within 30 calendar days.

The Subsystem Managers will be responsible for implementing all approved baseline technical/design basis changes to the official nEDM Project technical baseline documents and supporting technical design documents and files at all locations.
The change-control thresholds are identified in Table 11.

Table 11. nEDM Project Change-Control Thresholds

Level	Cost	Schedule	Technical Scope
DOE-SAE (Deviation Threshold)	25% increase to TPC (total estimated cost).	≥6-month increase (cumulative in a project-level milestone date).	Changes to scope that affect mission-need requirement.
DOE-NP	Any increase in the TPC **OR** a cumulative allocation of >$500K contingency.	≥3-month delay of a Level 1 milestone date.	Change of any WBS element that could adversely affect performance specifications.
DOE-LASO Federal Project Director Level 2	A cumulative increase of >$200K in WBS Level 2 **OR** a cumulative allocation of >$200K contingency.	>1-month delay of a Level 1 milestone date **OR** >3-month delay of a Level 2 milestone date.	Any deviation from technical deliverables that does not affect expected performance specifications.
nEDM Contractor Project Manager Level 3	Any increase of >$50K in the WBS Level 2	>1-month delay of a Level 2 milestone date.	Technical design changes that do not impact technical deliverables.

6.2 Configuration Control

All engineering will be done with modern 3D-modeling programs such as Unigraphics, Pro-Engineer, etc. that have been used to develop the conceptual design of the nEDM experiment. CAD tools are approved by the Chief Engineer. Communication between different products will be made by step translation, a proven technique. The official version of the reference design will be part of a Unigraphics model.

A computer program, Teamcenter, will be used to coordinate the disparate sources of engineering. Teamcenter is analogous to a code management system in software development. The project is broken into relatively small pieces. When an engineer wishes to do design on a piece, the relevant piece is checked out from Teamcenter. While it is checked out, no other engineer can have a changeable copy of the same piece of the model. Reference copies are allowed. When the design is complete, the engineer returns the completed piece of the model to Teamcenter, making it available to anyone else who needs it. It is the responsibility of the Chief Engineer to verify that the completed design matches the other parts of the project and is properly registered in Teamcenter. The Technical Coordinator consults as needed on scientific issues, especially in the area of subsystem conflicts. In this way, the Chief Engineer and the Technical Coordinator manage the integration of the nEDM experiment. The checking out and in processes are managed by the designer.

One area of special note is the heat budget. The difficulty of a cool-down/warm-up cycle and remotely diagnosing heat leaks makes adherence to the heat budget crucial. When the pieces of the experiment are assembled, any one subsystem can cause the entire project to be delayed significantly if the heat budget is not kept. Hence, the integration of the cryogenic components needs special attention. Acceptance tests that convey a high sense of reliability will be conducted by subsystem workers before any subsystem is integrated into the full apparatus. Cryogenic operation of a detector with this volume in the 500 mK range is outside the normal experience of most members of the nuclear physics community. The Technical Coordinator is a cryogenics specialist with experience in most other technical areas of the project. Mechanical, cryogenic and scientific integration of all parts of the subsystem is a requirement to pass a quality assurance review of an acceptance test.

When pieces of the project are converted to shop drawings for the manufacture of parts, these drawings are to be archived in the SNS electronic drawing-archive system. The SNS has agreed to accept nEDM drawings, and the nEDM Project will adhere to SNS drawing and identification standards. It is currently believed that the PDF format will have the greatest longevity. The Chief Engineer or a designer will check that engineers keep the archive up to date. In this way, as-built drawings of the apparatus will remain available to the collaboration for the duration of the project and ensuing scientific program.

7. Analyses, Assessments and Plans

7.1 Environment, Safety and Health

The principles of integrated safety management (ISM) will be incorporated into the project planning and execution. A primary objective of this project is to protect the environment and the safety of workers and the general public. This will be accomplished through

- defining the work and the potential hazards
- analyzing potential hazards
- developing and implementing hazard controls
- performing work within controls
- providing feedback and continuous improvement

The safety and environmental hazards associated with this project are documented in the *nEDM Preliminary Hazard Identification and Analysis*. This document will be finalized at CD-2. There is no serious safety issue associated with the nEDM project. The most commonly encountered hazards will be oxygen deficiency, vacuum, pressure, cryogenic, and elevated work hazards, all of which have standard mitigations. All work will be performed in a manner consistent with SNS safety policies. The nEDM Federal Project Director is responsible for approving safe operating procedures in accordance with DOE orders.

Since fabrication and assembly will take place at collaborating institutions, the nEDM management team will require that each institution follow their own safety policies, the principals of ISM and the controls described in the nEDM safety document in order to protect project personnel, equipment and the environment. The agreement to abide by the nEDM Project safety practices will be part of the MOU between the project and the collaborating institutions that will be in place before CD-2. The CPM will perform informal management inspections during visits to the construction sites to promote the project safety program.

The environmental consequences of SNS instruments, including IDT instruments, were addressed in the SNS Environmental Impact Statement (DOE/EIS-0247). No additional National Environmental Protection Act (NEPA) documentation is required.

7.2 Quality Assurance

A nEDM Project Quality Assurance (QA) Program, in accordance with DOE requirements, will be implemented. Prior to CD-2, the nEDM project team will define a nEDM QA plan. The plan will classify in grade levels how poor quality can impact the project, and then, associated with these grade levels, a set of actions to control and maintain quality. The plan will also define responsibilities of the QAM.

7.3 Risk Management

The nEDM Project uses a formal, systematic process for the management of risk. This process is compliant with the intent of DOE Order 413.3 and recognized best practices. Project risk will be managed according to the *Preliminary Risk Management Plan*. This plan recognizes that risk is not a one-time event, but is a dynamic, ongoing reality throughout the life of the nEDM Project. The plan indicates that the evaluation of overall risk is the simultaneous evaluation of likelihood of occurrence and impact of a potential risk. The likelihood table uses probabilities that are standard for NP projects. The impact table is similar to other projects but employs a boundary between marginal and significant impact defined by the minimal performance specifications defined in the CDR, some of which are reproduced in Table 1.

Within the project, the subsystem manager has a key role in identifying, assessing, and mitigating risks within their assigned WBS areas of responsibility. The risks are recorded in a log along with the suggested mitigation technique. The most commonly selected techniques were control, acceptance, avoidance, or transfer. To give a single example, the higher risk associated with the futures price of nickel can be avoided by buying as soon as possible. The risk log only contains high or medium impact risks. There were 5 high and 26 medium risks identified by the subsystem managers. The CPM identified three medium level risks that were project wide: unknown scope increases due to incomplete R&D, failure of the R&D to complete on schedule at the end of 2007, and a failure of some subsystem to meet its heat budget.

The R&D subsystem has had its risks evaluated via a separate methodology as described in the *Risk Based R&D Plan*. The principal difference is a modified impact table designed to evaluate risk in terms of impacts on the sensitivity of the experiment. This table employs the nEDM optimal specifications in its definitions. Six high level risks have been identified in the R&D, all of them technical. They are measurement of the ^{3}He-polarization relaxation time, design of the light collection system, valve development, high voltage studies, ^{4}He evaporative purification, and ^{3}He injection. The only mitigations to these risks are to execute the R&D using the best scientific techniques and to continue to evaluate alternate methods of achieving the same goals. Each R&D activity has clearly defined objectives.

Until the R&D questions are resolved, the overall nEDM Project Risk is high overall. The high risk is justified by the exciting science that is expected to result from the experiment. Under the assumption of fully successful R&D measurements, the overall project risk can expected to be reduced to medium at CD-2. The R&D program to date has dealt with the most severe in-principal risks developed years ago by the co-spokespersons. In every remaining case, there is a sound scientific reason to believe the risks can be resolved favorably and accounted for by the design, but it is not entirely ruled out that the R&D will uncover a crucial difficulty.

The technical risk is the highest contribution as noted above. The cost and schedule risks are judged to be moderate because the risk is reflected in the significant contingency allotted to each. The specifics of the technical risk follow.

The high extant technological risks are:
- The ^{3}He relaxation time
- ^{3}He injection
- The light collection efficiency
- Valve reliability
- ^{4}He evaporative purification

- High voltage attainable at 0.5K

The CPM has appointed an advisory committee of senior scientists from around the collaboration to advise him on the focus and progress of the R&D. The members are Jan Boissevain (Consultant – Chief Engineer), Mike Hayden (Simon Fraser), Bob Golub (NCSU), Geoff Greene (Tennessee/ORNL), and (Steve Lamoreaux (Yale – co-spokesperson). There advice has led to a number of actions by the CPM.

The reference design has many appealing and simplifying features. However, in the case a technological barrier is encountered, alternatives exist. The technical alternatives under consideration include:

- Placement of the PMTs inside the cryostat at 4 K or outside at room temperature;
- Use of laser fluorescence to supplement ordinary light collection;
- Pressurization of the liquid helium to increase the HV attainable;
- Alternate designs for controlling superfluid-helium film flow;
- The heat flush method of ^{4}He purification if the evaporative method fails; and
- A variety of valve designs to meet the varying needs and high reliability required by the project

7.4 Value Engineering

Value engineering will be incorporated into all phases of the nEDM design. A key feature is our continual review of our design to find simplifications that will reduce risk and cost. A key example mentioned earlier is the replacement of the mechanical bellows to move LHe with diffusive movement of ^{3}He.

At the October 5-7, 2006 collaboration meeting, one full day was spent looking for design simplifications. Two areas were identified that require further technical study. They are the high voltage feed and an alternate design for the polarizing beam guides. The potential for savings is $400k and $50-250k, respectively.

8. Project Monitoring and Reporting

The nEDM Project Office will evaluate performance based on the judgment of the subsystem managers and work package leaders. Subsystem managers will file brief, written reports on a monthly basis with the project office giving their estimate of the fraction of completion for ongoing activities. Progress will be evaluated based on the completion of milestones. Level 1 and 2 milestones have been documented in this PPEP. The level 3 milestones will be developed prior to CD-2.

The CPM will

- report monthly on progress to the LANL Physics Division Leader
- and the FPD will participate in monthly and quarterly reports to the DOE Office of Nuclear Physics, SC-26. The CPM will meet weekly with the FPD to discuss progress on the project. The CPM will assist the FPD in the preparation of quarterly reports. The nEDM MIE Project has been entered into the Project Assessment and Reporting System (PARS).
- meet weekly with the PCA to evaluate project monitoring systems and to discuss impending actions. They will prepare variance reports and change requests as needed. They will keep files of all useful documents.
- use collaboration and executive committee meetings to ensure effective communications and to resolve issues. Reviews of designs and acceptance tests will be held as needed to insure quality.
- lead the collaboration in responding to reviews by SC-26, either annual or critical decision reviews. Formal project reporting is in effect for the duration of the project, in accordance with the reporting requirements identified in DOE O 413.3 and this PPEP.

9. Transition to Operations

Once the nEDM Project is complete, the responsibility for completion of the scientific program will be transferred to the scientific co-spokespersons and the Executive Committee of the nEDM Collaboration. The maintenance of the apparatus will be managed by the physics department of ORNL with a budget of $250K/yr, which was discussed in the section on life cycle costs. An oral agreement is in place with the ORNL physics department that will be documented in an MOU before CD-2. The steady-state costs appear to be consistent with discussions between ORNL and DOE. During the 1-2 year period from CD-4 (mid-FY'13) to steady state operations, roughly $700k of commissioning costs will be needed at ORNL. Over this time, an amortized fraction of the steady-state support can be subtracted from the $700k assuming ORNL continues to use the university-based technicians employed by the nEDM project. If ORNL switches to ORNL employees, the $700k cost will need to be corrected for the difference in labor rates.

Though the salary of the ORNL cryogenic physicist is not part of the nEDM project, it is assumed that this individual will work nearly full time on nEDM commissioning. Following commissioning, the need will be reduced to ½-FTE.

The subsystem managers will be responsible for bringing the individual components on line, to support integrated operation of the complete system, to demonstrate and address the operating procedures and maintenance requirements of the equipment, to provide operational documentation, and to provide the necessary technical personnel and operator training and qualification.

10. Lessons Learned

Lessons-learned discussions will be initiated after CD decisions are rendered by the DOE to ensure full understanding of the nEDM Project feedback provided by DOE. Near the conclusion of the nEDM Project, lessons learned of "*what went right*" and "*what went wrong*," as well as insights into what might have been done better, will be assessed and documented.

Appendix A – WBS Dictionary to Level 3

1.1 Research and Development The R&D program is the experimental verification of the techniques proposed to execute the EDM experiment. It has been going on since 1997 and is scheduled to conclude at the end of calendar 2007. Each piece of the plan must either demonstrate the feasibility of the relevant technique or provide a selection amongst alternatives. The current funding is a mixture of project funds and LANL LDRD. Refer to the R&D plan.

1.1.1 Critical R&D R&D done in FY'06

1.1.2 Critical R&D prior to CD-2b R&D done in FY'07

1.2 Polarized Neutron Beamline & Shielding

1.2.1 Modeling The modeling of the neutron guide using standard MC ray-tracing techniques will server as the main input for the design. MC codes have already been developed by the collaboration. The task consists of detailed computer modeling of the polarizer and splitter to optimize the design by maximizing the neutron fluence in the cells and the polarization of the neutrons. Possible interactions with the target HV and cryogenics needs to be considered. Preliminary and final results will be documented in technical notes so that they can be used by other collaborators. Further the results will serve as input for the engineers/designers at ORNL for the design of the guide.

1.2.2 Design The neutronics design encompasses the design of the cold neutron guide for the EDM experiment (~15m), the magnetic guide field for the polarized neutrons, and the spin flipper. The neutron guide will be a continuation of the SNS-FPNB and transport cold (8.9A) neutrons to the target. The last ~14 m of the guide will serve as a polarizer with the goal to manipulate the neutron spins in such a way that they will point in the proper direction inside the target region. This will be achieved by means of a combination of magnetic and non-magnetic coatings (supermirrors) inside the guide system and magnetic fields. The cold neutron guide system will include guides, a secondary shutter, vacuum housings, supports, alignment jigs, etc. as well as all interfaces between these components. It is anticipated that the detailed design of the complete guide system will be performed as part of a "Design/Build" contract with the neutron guide manufacturer. Thus, the design task includes only the development of a detailed specification of the requirements for the cold guide system that can be given to the guide manufacturer to create the system design.

1.2.3 Procurement Neutronics refers to all aspects of the neutron beam transport system including neutron guides, secondary shutters, polarizers, as well as the mechanisms and supports associated with them. Some of these elements will be procured as complete systems, often including installation. In other cases the elements will require manufacture. The EDM beamline components include all parts of the neutron transport system for the last ~15 m of the FNPB , including guides, secondary shutters, polarizer, beam splitter, etc., as well as supports and alignment systems. The EDM neutron guide will be a continuation of the SNS-FNPB with an immediate transition to the polarizing guide. The polarizer will consist of a magnetizing supermirror (using vertical magnetization) that selects either "up" or "down" neutron spin states. The neutrons will be transported via a beam splitter to the two target cells. Polarizer and beam splitter are considered being a part of the neutron guide and will be fabricated by the vendor.

1.2.4 Installation Neutronics refers to all aspects of the neutron beam transport system including neutron guides, choppers, secondary shutters, monitors, polarizers, and beam stops, as well as the mechanisms and supports associated with them. The EDM beamline components consists of all parts of the neutron transport system downstream of the end of the FNPB, i.e. the last ~15m. This includes guides, secondary shutters, polarizers, as well as supports and alignment systems. Installation and test of the cold neutron guide and supports, secondary shutter, polarizing sheets will be performed by the contractor supplying the guide.

1.3 Cryostats, Refrigerators and Related Equipment The purpose is to design, procure, test and install a device that will enclose the neutron EDM experimental apparatus at cryogenic operating temperatures for times sufficient to complete the anticipated measurements. The cryovessel will include ports, feedthroughs and pumping lines necessary to connect to the experimental apparatus from room temperature. In addition, the task includes the design, procurement, testing and installation of the large container that will hold the liquid helium used to electrically insulate the measurement cells.

1.3.1 External Cryogenic Vessel, Intermediate and 4 K Shields The cryovessel will include an external pressure vessel to contain all of the experimental equipment, refrigerators, and cryogenic fluids under conditions of low temperatures ($T_{operation}$) for periods needed for the neutron EDM measurements. The external vessel will contain two intermediate temperature shields to reduce heating from infrared radiation to the target volumes. A large reservoir will store liquid helium at atmospheric pressure for the refrigerators and for cooling of the shields. The cryovessel must be able to maintain high vacuum for insulation, have little magnetic effect on the experiment and produce minimal radiation backgrounds in the operation of the experiment. The cryovessel will have appropriate connections for electronic sensors and for cryogenic fluids.

1.3.2 Helium Electrical Insulation Volume The helium electrical insulation volume is a non-magnetic enclosure which will house the ^{4}He target cells, the electrostatic plates and charging apparatus, the magnetometers, and the superfluid helium insulation material.

1.3.3 Refrigerators A combination of refrigerators (helium liquifier/refrigerator, ^{4}He evaporation, ^{3}He evaporation and/or ^{3}He -^{4}He dilution) will cool the target and insulation volumes to the operating temperature.

1.3.4 Cryovessel Sensors and Controls The cryovessel will be outfitted with thermometers to measure temperatures of all relevant sections of the shields, insulation volume, helium reservoir and refrigerators. The thermometers will be connected to appropriate wiring and cryogenic/vacuum feedthroughs to room temperature electronics, which can be interfaced to the experiment data acquisition system. There will be similar installations of heaters, pressure sensors, vacuum sensors and liquid helium level sensors with wiring, feedthroughs and external electronics.

1.3.5 Cryovessel Assembly, Testing and Operation Infrastructure The design, construction and testing of the cryovessel system will be supported by the preparation of the cryovessel infrastructure, installation of the cryovessel support structure, assembly of tools and components necessary for operation, and authoring and collection of documentation, including safety documentation and procedures.

1.3.6 Assembly and Testing of Cryovessel and Refrigerators The cryovessel, insulation volume, refrigerators and sensors will be tested at room temperature, at two intermediate temperatures, and $T_{operation}$ before the installation of components from other WBS units. The system must meet specifications for temperature, cooling power, cooldown time and vacuum integrity.

1.4 ^{3}He Services The ^{3}He Services (He3S) Subsystem is responsible for the management and control of purified liquid ^{4}He and polarized ^{3}He during the measurement cycle. The block diagram below illustrates the major components of this subsystem. The bulk of this apparatus consists of custom built, one-of-a-kind items. Special materials will be used that are chosen to be non-magnetic, non-superconducting, 3He “friendly” and not readily activated by neutrons. The materials requirements and lack of off-the-shelf components imply that a large engineering effort will be required. These items will be separately tested to check the purification, 3He injection, and pressurization functions. Subsequently, a final test of the performance the full system will be carried out. Also included in the scope of this subsystem is the refurbishment and instrumentation of a bulk helium purifier based on the McClintock "heat flush" mechanism.

1.4.1 ^{3}He Atomic Beam Source (ABS) The ^{3}He Atomic Beam Source (ABS) is a currently-existing apparatus, which will provide highly polarized ^{3}He atoms for injection in the Collection System (WBS 1.4.3) via the ABS Interface (WBS 1.4.2). It consists of a ^{3}He atomic beam source, a polarizer beam-line, and associated vacuum systems and diagnostic instrumentation. This task encompasses the effort necessary to adapt the ABS to the nEDM experiment, including its mechanical support, the vacuum interface, and in-situ ^{3}He beam flux measurement.

1.4.2 ABS Interface The ABS Interface provides the connection between the ^{3}He Atomic Beam Source (ABS) and the collection volume. It must be thermally intercepted so that the heat load from the room-temperature ABS on the roughly 0.3 K collection volume is not excessive. A magnetic field must adiabatically rotate the spins of ^{3}He atoms from the direction of the axis of the ABS (inclined at roughly 45 deg) to horizontal, while gradually reducing the field to the milliGauss level in interior of the nEDM cryostat. A film killer in the ABS interface will reduce the heat and vacuum load associated with the super-fluid helium film from the collection volume. The interface must accommodate thermal contraction during cooldown without disturbing the ABS-collection volume alignment.

1.4.3 Polarized ^{3}He Collection System The ^{3}He Collection System provides the environment in which polarized ^{3}He delivered by the ABS Interface (WBS 1.4.2) from the ABS (WBS 1.4.1) is injected into purified liquid ^{4}He. The collection system must maintain the ^{3}He polarization without significant relaxation until the prepared sample is delivered to the measurement cell. The temperature of the collection system will be that of the measurement cell. A cos(θ) coil (not part of this task or subsystem) maintains the proper holding field. A SQUID-based NMR system will be used to measure the filling and final polarization of the ^{3}He in the collection volume. The outlet of the Collection System connects to the measurement cell via the Collection Isolation (V4) Valve (1.4.10.4).

1.4.4 ^{3}He Injection Test The Injection Test involves a the ABS (WBS 1.4.1), the ABS Interface (WBS 1.4.2), the Collection System (WBS 1.4.3), and the Collection Isolation Valve (V4) (WBS 1.4.10.4). ^{3}He from the ABS will be injected into purified ^{4}He and the resulting accumulated polarization will be measured. This test will be carried out using a separate cryostat. There will be no additional magnet shielding.

1.4.5 Purifier The purifier employs a technique based on the high mobility of ^{3}He atoms and their preferential evaporation at temperatures below 0.6 K, to remove ^{3}He and, in so doing, re-purify ^{4}He from the measurement fraction of 10^{-10} to less than 10^{-14}. Evaporated ^{3}He is pumped away using an absorption pump. Two such purifiers will be installed in the experiment so that one can be operated while the absorption pump of the other is regenerated. An external vacuum system is needed to remove ^{3}He during the regeneration process. Apparatus will be included to allow the purity of the resulting ^{4}He to be measured or inferred. Purifier isolation valves (V6) (see WBS 1.4.10.6) and a volume displacement system (WBS 1.4.6) are used to direct fluid to be purified to one of the purifiers.

1.4.6 Purifier Volume Displacement A volume displacement bellows will be used to elevate the LHe level in one or the other of the purifiers (WBS 1.4.5). The purifier into which the LHe flows is selected by opening the corresponding Purifier Isolation (V6) valve (WBS 1.4.10.6). This task encompasses effort required to design and fabricate the bellows and associated actuator.

1.4.7 Purifier/Valve Test The aim of this task is to perform an independent test of purification, purifier regeneration, and LHe fluid management. The test will involve the results of the Purifier (WBS 1.4.5) and Volume Displacement (WBS 1.4.6) tasks as well as the Purifier Isolation Valves (V6) (WBS 1.4.10.6), the Purifier Control Valve (V5) (WBS 1.4.10.5), and the Volume Displacement Interconnect Plumbing (WBS 1.4.11.1). Additional sensors, and plumbing as well as a special cryostat will be needed for this test.

1.4.8 Pressurizer In order to attain sufficient electric field in the measurement cell, the LHe pressure must be raised to 1 atm. This is accomplished by reducing the volume by a factor of about 1.1%. The bellows and associated actuator which accomplishes this volume reduction is the scope of this work package. Because the bellows is in contact with LHe in the measurement cell, it must be made of ^{3}He "friendly" material. The Pressurizer interfaces to the rest of LHe plumbing via the Pressurizer Isolation valve (V2) (WBS 1.4.10.2).

1.4.9 Pressurizer/Valve Test The scope of this task is the effort and material required independently test the operation and reliability of the Pressurizer (WBS 1.46.8), the Pressurizer Isolation Valve (V2) (WBS 1.4.10.2) and the Pressurizer Standoff Valve (V3) (WBS 1.4.10.3). To perform the test, a special test cryostat and interconnect plumbing must be constructed. In addition, the test will require temperature and pressure instrumentation.

1.4.10 Valves The design and fabrication of valves required to control the flow of LHe at 0.3K during the measurement cycle are the focus of this task. The following valves and their associated actuators are included: one Pressurizer Isolation (V2) Valve (WBS 1.4.10.2), one Pressurizer Standoff (V3) Valve (WBS 1.4.10.3), one Collection Isolation (V4) Valve (WBS 1.4.10.4), one Purifier Control (V5) Valve (WBS 1.4.10.5), and two Purifier isolation (V6) Valves (WBS 1.4.10.6). Also included in this task is the actuator and an interface to the two Cell Isolation (V1) Valves (WBS 1.4.10.1) (but not the valve stems and seats). A pneumatic system with gaseous helium at 0.75 atm. as the working fluid (a so-called "heliomatic" system) is planned for the connection which transmits force between mechanical links from 300K to 4K and from 4K to 0.3K.

1.4.11 Interconnect Plumbing Interconnections between components of the Helium-3 Services (He3S) subsystem and the measurement cells will be accomplished by plumbing segments provided as part of this task. Where polarized ^{3}He is present, materials must be ^{3}He "friendly", and a holding field must be provided, typically by a solenoidal coil surrounding the plumbing segment. Connections to valves at the ends of the plumbing segments must be superfluid LHe tight. Three segments are included in this task: the Volume Displacement Interconnect (WBS 1.4.11.1), the Collection/Purifier Interconnect (WBS 1.4.11.2), and the Pressurizer/Cell Interconnect (WBS 1.4.11.3).

1.4.12 He3S (Full Subsystem) Test The scope of this task is a full system test of all components of the Helium-3 Services (He3S) subsystem. The aim is to perform a practice-installation and then to test all components of the subsystem during simulated measurement cycles with the goal of confirming that the subsystem meets the nEDM experiment specifications. A special cryostat and test measurement cells will be needed for the test. Instrumentation for measuring ^{3}He polarization in the test cell is also included.

1.4.13 He3S Installation in Upper Cryostat This task includes the effort and material required to perform the final integration of the Helium-3 Services (He3S) subsystem components into the rest of the nEDM experiment at NCSU or ORNL. Disassembly and shipping of components to the final assembly area and not included within the scope of this task.

1.4.14 McClintock Purifier (Bulk Purified ^{4}He) The scope of this task is the complete refurbishment of the McClintock Purifier for production of bulk purified ^{4}He. It includes replacement of all hardware borrowed from elsewhere for early tests of the purifier. Also included is a final commissioning of the purifier. Actual production of purified ^{4}He for tests of components of the He3S subsystem or the nEDM experiment is not part of this task.

1.5 Magnets & Magnetic Shielding This subsystem includes the design, construction and commissioning of all the constant and time varying magnets needed for the experiment. It also includes the four-layer shield, superconducting shield and ferromagnetic shield.

1.5.1 Four-Layer Conventional Shield The entire experiment (both the upper and lower cryostat) will be enclosed within a cylindrical four-layer μ-metal magnetic shielding structure held at room temperature. The proposed shields are very large with the largest cylinder having a diameter and length of ~8 feet and ~21 feet, respectively. We anticipate procuring the shields from Amuneal, a Philadelphia-based vendor specializing in magnetic shielding, and we have already begun preliminary discussions with this company regarding the design, cost, and construction schedule for the shields. The final design of the shielding structure will be driven by the overall size of the experiment, the locations and sizes of all needed penetrations, and design/engineering considerations for integration of the shielding structure into the entire experimental apparatus. Therefore, final negotiations with Amuneal for construction and delivery of the shielding structure will be possible only after the experimental design has been finalized. The cost (and weight) of the shielding structure scales ~linearly with the layer thickness. Based on preliminary discussions with Amuneal, we anticipate a 6 to 12 month lead time for construction and delivery of the shielding structure. Due to their large size, the shields would be shipped in smaller pieces to the experimental site, thus requiring some amount of on-site assembly (including integration of structural re-enforcements; projected weight of the structure is ~5 tons).

Several magnetic penetrations through the outer four-layer μ-metal shield and the inner ferromagnetic shield will be necessary (i.e., transport of neutrons and polarized 3He, access to the inner cryostat, etc.). The design and placement of these magnetic penetrations will need to be carefully studied in order to determine their effect on the magnetic field uniformity and outer fringe fields. For example, "snouts" may need to be placed around the penetrations in order to preserve the uniformity within the shield. Further, a final decision on the penetrations will require a considerable amount of design/engineering efforts in order to ensure that the penetrations are compatible and serve all of the experimental needs. It will be important that this activity is completed in a timely fashion so that the final orders for the magnetic shielding can be placed with the appropriate vendors.

1.5.2 Superconducting Shield Residual magnetic fields penetrating the four-layer conventional (μ-metal) magnetic shielding structure will be expelled by a cylindrical superconducting lead shield mounted in between the 4K shield for the cryostat and the inner 4K ferromagnetic shield. The proposed shield is fairly large, with a diameter of ~50", a length of ~157", a thickness of ~0.050", and an estimated weight of ~700 pounds. The final design/dimensions for the superconducting shield will be driven by the size of the cryostat, and design/engineering efforts will be needed to integrate the shield into the overall design of the cryostat.

1.5.3 Constant Field Coil Inner Ferromagnetic Shield The experiment will employ a conventional cylindrical ferromagnetic shield for the innermost layer of the magnetic shielding located in the 4K region. The proposed shield has a diameter of ~49" and a length of ~156". Several different ferromagnetic materials are being considered for this 4K shield. We believe a viable candidate material for this shield is Cryoperm, a high nickel content alloy specially designed by Amuneal for high shielding performance at cryogenic temperatures. Another alternative is Metglas foil, a material that can be wound onto the surface of an aluminum support structure.

1.5.4 B_0 Field Coil and Gradient Field Coil The constant field coil will be used to generate a uniform DC magnetic field over the volume of the measurement cells. A small gauge conductor will be wound onto a cylindrical aluminum support structure with the wire spacing chosen to emulate a cos θ surface current distribution. A DC power supply will be used to power the constant field cos θ coil. This power supply must have a temporal stability of one part per million, which will require procurement of a highly-stable power supply along with the design and construction of a stabilization circuit.

1.5.5 π/2 Coil The π/2 coil will be used to generate a pulsed AC field designed to simultaneously rotate the 3He and neutron spins through 90 degrees. A solenoidal or cosθ winding onto an aluminum support structure will generate a magnetic field perpendicular to that generated by the constant field cos θ coil. A pulsed AC source will be used to drive the π/2 spin-rotation coil. This AC source will be operated in the low-frequency (several Hz) regime.

1.5.6 Dressed Spin Coils The dressed-spin coils will be used to modify the effective g-factor of the ^{3}He atoms and neutrons via application of an appropriately tuned AC field. The design for these coils will be essentially identical to that for the constant field cos θ coil except that they will be rotated by 90^o with respect to the constant field coil. Two nested coils with currents offset in phase by 180 degrees will be needed in order to reduce heating of the 4K ferromagnetic shield due to Eddy currents. AC power supplies will be used to drive the dressed spin coils.

1.5.7 ^{3}He Spin-Holding Coil The 3He spin-holding coil will be used to generate a DC holding field for the polarized 3He. It will also be a cos θ coil with a ferromagnetic shield. This coil is significantly smaller that the constant field coil. A DC power supply will be used to drive the 3He spin-holding coils.

1.5.8 3He Spin-Holding Coil Ferromagnetic Shield The 3He spin holding coil will employ a conventional cylindrical ferromagnetic shield located in the 4K region. The proposed shield has a diameter and length approximately 1" larger that the spin holding coil (WBS7.8). Several different ferromagnetic materials are being considered for this shield. We believe a viable candidate material for this shield is Cryoperm, a high nickel content alloy specially designed by Amuneal for high shielding performance at cryogenic temperatures. Another alternative is Metglas foil, a material that can be wound onto the surface of an aluminum support structure.

1.5.9 Field Monitors The field monitors will provide *in-situ* field monitoring of the AC and DC magnetic fields. These monitors will include cryogenic fluxgate magnetometers for installation in the 4K volume and room temperature magnetometers to monitor the ambient fields and shielding factor. An automated mapping system will translate the monitors throughout the sensitive volume, and a data acquisition system will record the field values as a function of position and time.

1.6 Central Detector System The Central Detector Systems (CDS) is situated at the heart of the experiment, and include the measurement cells and the 3He valves, the scintillation light transport and detection system, the SQUID magnetometers, the beam stop and neutron shield and the HV electrodes, HV generating system, and HV monitoring system.
The scope of this subsystem includes the design, procurement, and installation of the above subcomponents. Also, constructing appropriate apparatus to conduct tests of these subcomponents, and performing the tests itself are also part of the scope of the subsystem.

1.6.1 Preliminary Design Coordination Coordination of preliminary design activities of all the work packages that belong to this subsystem. Since this subsystem contains many work packages, and the design, procurement, and installation of different work packages will be done at different institutions, it is of critical importance to the success of the project to have a well coordinated and organized initial design effort.

1.6.2 HV system The electric field applied to the measurement cells will be supplied by electrodes that sandwich the measurement cells. The electrodes are charged up by the variable gain capacitor. The scope of this subsystem is to design, procure, and install the gain capacitor, the electrodes, the penetration (the mechanism to bring the HV in from external power supply) and the connecting cables.

1.6.3 Kerr Rotation HV monitor The electric fields in the measurement cells and in the gain capacitor will be monitored by an electric field monitor that is based on the measurement of ellipticity of a polarized light due to the Kerr effect.
The scope of this work package is to design, procure, and install the electric field monitor based on the Kerr effect measurement.

1.6.4 Measurement cells The measurement cells will hold the ultra-pure liquid helium that will be doped with polarized 3He at the beginning of each measurement cycle. The measurement cells will then be irradiated by the 8.9A cold neutron beam so that UCNs will be generated in the cells.
The measurement cells will be made of UVT acrylic. The front window will be made by deuterated acrylic to let the neutron beam pass through.
The scope of this work package is to design, procure and install the measurement cells.

1.6.5 SQUID System The magnetic field inside the measurement cells will be monitored by measuring the precession frequency of the polarized 3He atoms in the measurement cells. SQUID magnetometer will be used to pick up the precessing magnetization signal 3He.
The scope of this work package is to design, procure, and install the SQUID magnetometer, which includes the SQUIDs, pickup loops, and electronics.

1.6.6 Light system The precession of ultracold neutrons (UCNs) in the measurement cell will be measured using the spin dependent capture reaction between 3He and neutron. The scintillation light generated by the reaction products traveling in the liquid helium will be detected to measure the precession of UCNs. The scintillation light will be emitted in extreme ultraviolet and will be down-converted by the wavelength shifter coated on the cell walls. Then the light will be transported through the light guide to the PMT. We need 40 photoelectrons to be able to perform the particle ID based on the measurement of alterpulsing. The PMT will be placed in the 4K region to eliminate thermal breaks in the light guide to avoid light losses. The scope of this subsystem is to design, procure and install the light guides, the PMTs, and the PMT housing.

1.6.7 Insert end cap All the components in the central detector systems will be mounted on this end cap. Also all the feedthroughs and services will be mounted on the end cap. The end cap is part of the boundary between the 300mK helium and the insulation vacuum.
The end cap will have to be made of material that meets various requirements. It must not be activated by exposure to neutrons. It must not be superconducting at 300 mK. The scope of this work package is to design, procure, and install the end cap.

1.6.8 V1 valve The each measurement cell will be equipped with a valve that opens when 3He is introduced to the cell or is removed from the cell. The valve will have to be on the measurement cell wall to avoid unwanted depolarization of the UCN and 3He, UCN loss, and non-uniformity of the electric field. The scope of this work package is to design, procure, and install the V1 valve.

1.6.9 Beam Stop and Neutron Shield A beam stop and neutron shielding are necessary to remove unwanted scattered neutrons from the region around the measurement cells to minimize the activation of materials surrounding the cells. The beam stop and the neutron shielding will be made of neutron absorbing material such as boron nitride. The scope of this work package is to design, procure, and install the beam stop and neutron shielding.

1.6.10 Test apparatus A cryostat and a helium vessel will be necessary to test the completed central detector systems at Los Alamos prior to shipping out for the final assembly. The scope of this subsystem is to design, procure, and install the necessary apparatus to test the central detector system.

1.6.11 Central Detector System Integration and tests A thorough performance test of the entire central detector systems will need to be performed at LANL before we can ship the central detector system for the final assembly of the experiment. The scope of this work package is to integrate different components and to perform necessary tests to ensure that the necessary performance requirements are met.

1.7 Electronics, Simulations, Data Analysis This WBS element comprises four work packages: to develop a slow controls system for the EDM apparatus; to develop a data acquisition system for the EDM experiment; to carry out simulations of all aspects of the experiment; to develop analysis codes to process the large amounts of data obtained over the multi-year duration of the experiment.
EPICS (Experimental Physics and Industrial Controls System) is the proposed control system standard. EPICS software is now universally adopted for use at the major accelerator facilities (including the APS and the SNS). It supports many off-the-shelf commercial devices in a distributed network environment, and is freely available to interested users.
The data acquisition system will be built around coincidence-triggered wave form digitizers, capturing the prompt and after-pulse signals associated with neutron -3He capture events. Many terabytes of data can be expected to be accumulated over the lifetime of the experiment, and techniques for rapidly evaluating the data will need to be developed, along with reliable archival storage systems.
Simulation of all aspects of the experiment will be important to understanding the ultimate sensitivity of the apparatus, from neutron transport into the measurement cells, to optimization of the measurement cycle, to light production and efficient transport through light guides to the photomultiplier tubes. Of particular interest, and unique to the EDM experiment, are modeling of the neutron and 3He trajectories and their spin interactions in the magnetic and electric fields of the apparatus, and simulation of background suppression via detection of after-pulsing.

1.7.1 Slow Control System This work package is concerned with slow control of all aspects of the EDM apparatus. Work activities will take place at five different sites during the development and thus five independent control systems are required: cryogenics, magnets, 3He, inserts (including high voltage), and neutronics (including neutron flux monitors). The overall architecture of the system will be designed and communicated to the work package leaders so that system integration at the time of full assembly is not compromised by subsystem control incompatibilities. The basic architecture of each individual system will consist of an operator interface (OPI) made up of a Linux computer, or equivalent, and display monitors connected over a network to an input output controller (IOC) made up of either VME crate(s) with commercially available modules running under VxWorks, or an equivalent real time operating system and hardware complement. Subsystem managers will be asked as much as possible to purchase hardware compatible with existing device drivers or software. A central database of process variable (PV) definitions, or equivalent control parameter records, will be developed and communicated to all subsystem developers.

1.7.2 Data Acquisition System This work package is concerned with design, implementation and initial testing of the data acquisition (DAQ) system for the EDM experiment. The DAQ will incorporate wave form digitizers to sample the initial pulse from the capture of the neutron by 3He and after-pulses associated with the subsequent decay of the triplet state He molecules formed in the initial ionization. Sampling rates will be of order 1 GHz and sampling times will be of order a microsecond. The digitizers will be gated by appropriate logic coincidence signals derived from the photomultiplier tubes monitoring each of the two cells. The system will need to be capable of handling coincidence event rates up to 1 kHz. A fast logic system will also be implemented to allow for rapid diagnostic testing during the commission and data taking phases of the experiment. The DAQ will be tested using reactor or accelerator based neutron sources and appropriate scintillation detector systems. A cosmic ray suppression system will be developed and implemented if it is proven to be cost effective at the 90% rejection level.

1.8 Infrastructure The conventional construction of the EDM project is concerned with the integration of the EDM experimental apparatus into the EDM experimental hall at the SNS facility at Oak Ridge National Laboratory. This will cover the services to the experimental equipment, such as electrical, plumbing, gas, as well as the fabrication of mechanical platforms to allow for safe access to the experimental equipment. This section also includes designing and fabrication of jigs and fixtures for the experiment, these will allow for the installation as well as maintenance of the equipment. The last task included is the procurement and installation of a counting house facility in the EDM experimental hall.

Most of the engineering work associated with these tasks, will take place at Los Alamos, by engineers in P-25. The workers needed for the installation will be part of the EDM technical team, along with technicians from the SNS facility. Crafts work, electrical and plumbing associated with the experiment, will either be performed by crafts personnel associated with the SNS facility or contracted through the SNS facility. Their work will be supervised and approved by the SNS facility engineering representative. Rigging of equipment will be performed by SNS trained personnel.

1.8.1 Platforms The nEDM experiment requires working at a number of heights from the ground. Commercial platforms and interconnecting ladders will be purchased to allow working at heights safely to OSHA requirements and comfortably.

1.8.2 Electrical Plant The electrical plant refers to distributing electric power from the wall of the FNPBICN building to the areas surrounding the experiment where it is needed.

1.8.3 Plumbing Plumbing refers to distributing water, cryogens and other fluids around the experimental area.

1.8.4 Mechanical Supports Mechanical supports refer to the structures to support various pieces of equipment. The jigs and fixtures required to move pieces of equipment are also included.

1.8.5 Counting House The counting house is where the parts of the data acquisition system are held that must be near the detector.

1.9 Assembly and Commissioning This work package will bring together the tested components from the other work packages (Cryostat, Insert, 3He Components, Coil Package and Magnetic Shields and

DAQ) and assemble them together to form a complete apparatus. Once together and tested, a commissioning run will be performed to demonstrate completion of CD4 delivery specifications.

1.9.1 Coil Package Assembly/Installation at ORNL Subsequent to that successful commissioning of the insert, we will begin assembly of components from other work packages into this vessel. This work package covers the assembly and commissioning of the magnetic field coil package. Costs for this item are dominated by technician labor which is determined by the estimate for the required test duration. Costs were developed under the assumption that the coil package and related DAQ arrive at ORNL fully tested.

1.9.2 Insert Assembly/Commissioning at ORNL The cryostat will be constructed and tested at ORNL as part of a separate work package. We will begin by assembling measurement cell insert (including the high voltage system, light collection, squids, etc.) into the cryostat vessel. Costs for this item are dominated by technician labor which is determined by the estimate for the required test duration. Costs were developed under the assumption that the insert and related DAQ arrive at ORNL fully tested.

1.9.3 3He Component Assembly/Commissioning at ORNL Following the successful commissioning of the insert inside the cryostat, we will begin assembly of the 3He injection/purification system into the cryostat. Costs for this item are dominated by technician labor which is determined by the estimate for the required test duration. Costs were developed under the assumption that the 3He components and related DAQ arrive at NCSU fully tested.

1.10 Project Office The project office is responsible for managing the EDM project. The responsibilities include technical oversight, reporting to DOE, tracking cost and schedule, distributing funding, project integration, etc. The duties are described in detail in the PPEP, the Acquisition Strategy, and the Configuration Management Plan. The ORNL Operations Manager coordinates the work at ORNL as a local liaison. Project integration is controlled by the Chief Engineer, who coordinates mechanical issues, and the technical coordinator, who coordinates scientific issues – especially cryogenics matters. The ORNL Operations Manager is the individual responsible for coordinating all activities at the SNS. The paid positions at the project office will reduce their FTE fractions commencing in FY'2011 when the subsystems are largely complete, most of the budget has been expended, and the focus is on assembling the apparatus.